PONTIFICIA UNIVERSIDAD CATOLICA DE CHILE
ESCUELA DE INGENIERIA

DEVELOPMENT OF A SOLAR CELL AND ENVIRONMENTAL CHARACTERIZATION SYSTEM FOR ISOLATED LOCATIONS

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Memoria para optar al título de
Ingeniero Civil Electricista

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PONTIFICIA UNIVERSIDAD CATOLICA DE CHILE
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Departamento de Ingeniería Eléctrica

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RESUMEN

Este documento describe el diseño y desarrollo de una estación multipropósito para la realización de experimentos en lugares aislados. Se presenta su aplicación a un sistema para caracterizar celdas solares, adonde se requiere capturar datos eléctricos y ambientales. Esto permite evaluar el desempeño de nuevos dispositivos fotovoltaicos respecto a tecnologías convencionales, y a la vez hacer un análisis ambiental del entorno.

El sistema implementado incluye dos tipos de celdas solares de prueba sobre un sistema móvil capaz de orientarlas a posiciones arbitrarias, incluyendo la localización continua del sol. Se captura información de sus características de corriente/voltaje y sus temperaturas a lo largo del día, además de información ambiental incluyendo el espectro solar incidente, la irradianza total y variables meteorológicas.

La solución propuesta está basada en dos sistemas complementarios que interactúan entre sí. Se incorpora un sistema específico para la caracterización de celdas solares, el cual interactúa con un dispositivo genérico que le provee de energía, capacidad de procesamiento, soporte físico e interfaz con el usuario en terreno. Este diseño genérico permite que el sistema sea fácilmente ampliable para proveer servicios similares a nuevos dispositivos que se requiera incorporar en el futuro.

El trabajo presentado en este documento fue desarrollado para entregar información científica a las operaciones de terreno del proyecto NASA “Life in the Atacama” ejecutado por la Universidad de Carnegie Mellon en el desierto de Atacama (Chile) durante los años 2003, 2004 y 2005.

ABSTRACT

This work describes the methods and techniques used for the development of a multipurpose station to perform experiments in isolated places. Its application in a system to characterize solar cells is presented, where capturing of electrical and environmental data is required. Obtained results allow to compare the performance of new and conventional photovoltaic devices, and also to characterize the surrounding environment.

The implemented system incorporates two different solar cell technologies. They are installed on a mobile platform capable of orienting their position arbitrarily and perform continuous sun-tracking. Voltage, current and solar cell temperature data is logged together with relevant environmental information such as the incident solar spectrum, total irradiance and weather variables.

The proposed solution is based on two complementary systems that interact between them. It incorporates a specific device for solar cell characterization which interacts with a generic system that provides it with energy, processing power, physical support and user-interface in the field. As a consequence of this generic approach, the system can be easily expanded to provide analogue services to new devices that need to be incorporated in the future.

The described system was developed to provide relevant scientific data for field operations of the NASA-funded “Life in the Atacama” project performed by Carnegie Mellon University in the Atacama desert (Chile) during years 2003, 2004 and 2005.

1 BACKGROUND OF THE PROJECT

This document is developed as part of the NASA-funded “Life in the Atacama” project, executed by Carnegie Mellon University with the collaboration of Pontificia Universidad Católica de Chile among other institutions. The Life in the Atacama project seeks to develop technology in support of robotic astrobiology for NASA while conducting useful Earth science in the Atacama Desert of northern Chile [Wett03]. The final objective is to create technology relevant to the exploration of Mars in the form of an autonomous rover capable of traversing extremely long distances finding basic forms of life without direct human intervention.

This technical report covers all details related to the construction of a solar-powered and autonomous station for testing, which provides complementary engineering and scientific data for rover operations during field experiments. The main objectives of the station are: i) to characterize the electrical performance of Advanced Triple Junction (ATJ) n/p InGaP/InGaAs/Ge solar cells built for space applications in relation to standard silicon solar cell technology; ii) to provide tools for weather-characterization during field operations, providing relevant data for solar cell analysis, rover operation and scientific investigation; and iii) to be easily upgradeable to add new experiments or additional weather sensors in the future.

The developed system was built and tested during field rover operations of years 2003 and 2004 in the Atacama desert, near the cities of Iquique and Antofagasta (Chile). The final version of the autonomous station is completed to operate during the upcoming field season of 2005. The project was financed by the Robotics Institute of Carnegie Mellon University (CMU) being developed by students of the Electrical Engineering Department of Pontificia Universidad Católica de Chile (PUC) under supervision of professors of PUC and faculty of CMU.

2 OVERVIEW OF SYSTEM

System requirements detailed in Chapter 1 are accomplished by the development of two independent and interacting systems, the Multipurpose Autonomous Solar Station (MASS) and the Solar Cell Testing Unit (SCTU). The MASS is designed as a general-purpose device which provides basic services to "child" experiments[1] needing to operate in stand-alone mode. It interacts with the SCTU, which is a child experiment capable of characterizing multiple solar cell technologies by capturing electrical and environmental data.

The MASS is a solar-powered and general-purpose system designed to provide power, processing capacity, user-interface and physical support to one or more child experiments for long periods of time in isolated places. It offers hardware and software to control child experiments by capturing, filtering and displaying obtained results. Additionally, it provides power to devices through a power manager system with energy-saving capabilities. The system is capable of switching Off selected components when they are not in use and also to monitor the available energy in the system batteries. If there is no remaining energy in the system it performs a controlled emergency shutdown[2], maintaining the computer Off until the system batteries have been recharged. Furthermore, the MASS includes an onboard user-interface composed by an alphanumeric display and keypad to manually execute commands, change crucial execution parameters and monitor measured variables without using external devices. All MASS characteristics are discussed in Chapter 3.

---

[1] Child experiments are defined as electronic systems that need to be externally powered and controlled (e.g. data logging systems).

[2] A "controlled shutdown" takes into account the hardware and software context, exiting software routines, and even closing the complete operating system when necessary, prior to hardware disconnection. This is done to maintain the integrity of the file system.

The SCTU is a group of several independent logging tools that provide complementary information to characterize solar cells. Its objective is to analyze the performance of standard silicon solar cells compared to the newly commercially-available Advanced Triple-Junction (ATJ) n/p InGaP/InGaAs/Ge solar cells under equivalent environmental conditions. It continually logs current-voltage data (I-V curves) for the complete operation range and logs other possibly efficiency-correlated values such as temperature of the solar panels, irradiance, solar spectrum and weather data. All measurements are captured during different times of the day with the cells positioned to different orientations (fixed positions and continuous sun-tracking). The results of the SCTU provide relevant electrical data to compare new and old solar cell technologies, and data to quantify the benefits of a sun-tracking mobile system. Details of the SCTU, including individual experiments and captured variables are discussed in Chapter 4.

2.1 Block Diagram

The MASS and SCTU systems contain several controllers, instruments, sensors and actuators which are integrated to accomplish all of its requirements. Figure 2.1 shows the modules and interfaces that form the MASS and SCTU systems, including the control interface and power lines of the most relevant power-consuming devices. A complete description of the elements shown will be covered in detail in this document.

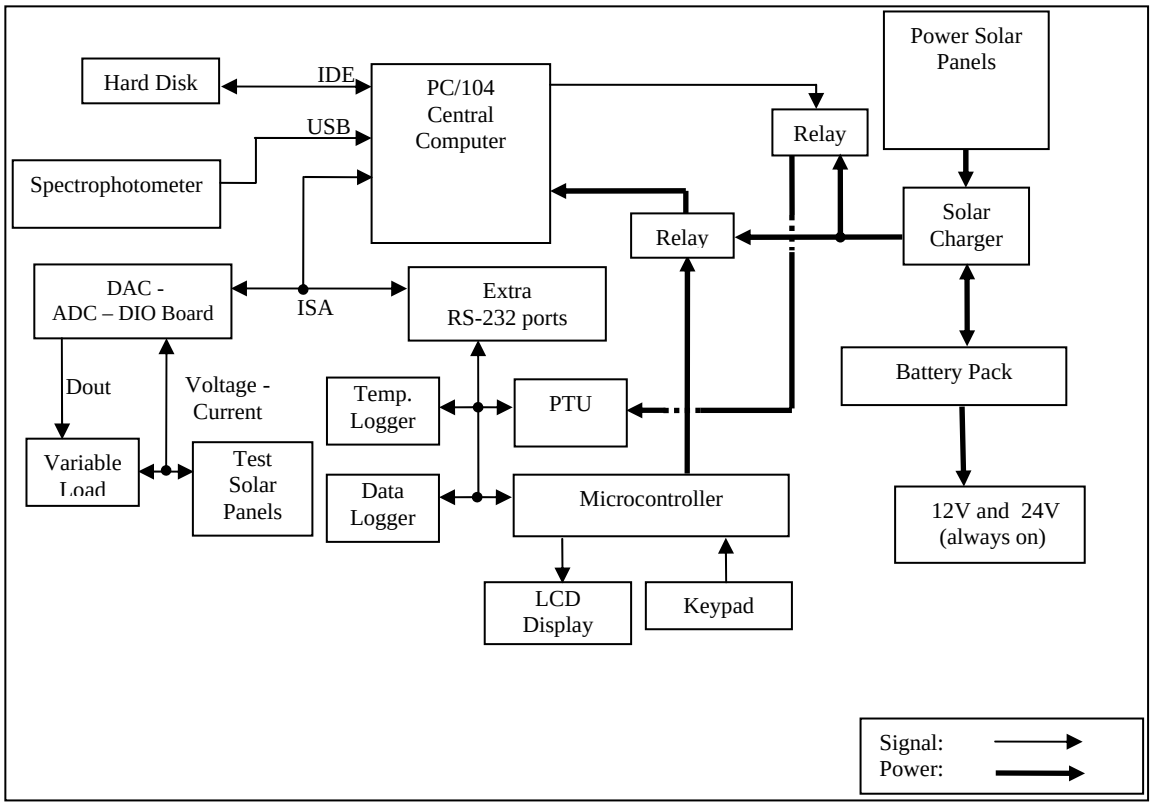

Figure 2.1: Block diagram of the system

3 MULTIPURPOSE AUTONOMOUS SOLAR STATION (MASS)

As discussed in Chapter 2, the MASS includes several hardware and software components that provide services to child experiments. These components are grouped into “modules” (or hardware-software units) which are available to child experiments as independent units to perform specific functions, as shown in Figure 3.1. The MASS additionally defines a “software core” which delineates all the basic rules for the software running on the MASS. All programs, including internal module software and external child experiment software must follow these rules in order to avoid potential conflicts.

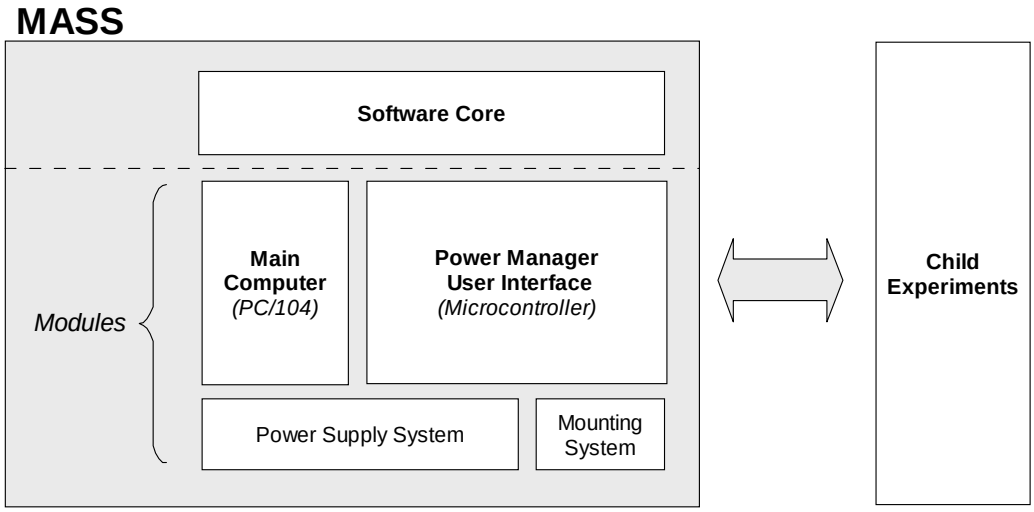

Figure 3.1: Internal structure of the MASS interacting with child experiments

3.1 MASS Modules

As shown in Figure 3.1, the MASS includes a main computer module, power manager/user interface module, mounting module and power supply system module. They provide child experiments with controlled power (when available), advanced processing capacity, logging capacity, input and output of analog and digital interfaces, physical storage space and user interface. Individual modules are

composed by one or more hardware units and include a control software (when applicable).

As this report mainly intends to document the most relevant concepts and techniques used in the implementation of a MASS system, details of specific components used will be omitted in the main sections of this report (only generic characteristics of the selected devices will be mentioned). Details of specific brands and characteristics of used devices are included in Appendix A.

3.1.1 Central Computer Module

The central computer module is based on a high-performance x86 CPU using the PC/104 form-factor. The PC/104 format was chosen due to its small-sized and stackable architecture which allows to add new hardware boards in a space-efficient way. The computer uses a laptop-type 3.5” hard drive and runs Redhat Linux operating system. Linux was chosen given its proved stability, solid networking capabilities and simple programming tools. The system provides processing and storage capacity to child experiments as well as to the power manager/user-interface module. Therefore, the main computer module of the MASS can be used to control child experiments and also to log and process their captured data.

In order to achieve the generic and expandable objectives of the MASS, the PC/104 standard stack was expanded with additional boards to include various widely-used analog and digital input/output (I/O) interfaces. Basic PC/104 interfaces were extended with an analog/digital (A/D) input/output board and with a multiserial RS232 / RS422/485 communications board.

The specific characteristics of the selected boards are an A/D interface with 32 analog inputs, 4 analog outputs and 24 shared digital I/O, and a multiserial board providing 8 additional serial ports. Considering the existence of a USB interface in the motherboard, the system provides child systems with most of standard interfaces available.

3.1.2 Power Supply System Module

The MASS provides power to its internal components as well as to child experiments. It offers several voltage outputs which may be uninterrupted for low-consuming devices, or relay-controlled for devices with high-power requirements or with short duty cycles.

The system obtains its power from a group of solar panels. The excess energy charges a set of batteries which power the system when there is no enough solar energy available. A solar controller is included, which automatically manages the energy available giving an optimal charging cycle to the batteries and also maintaining the power solar panels working at their maximum efficiency point by using pulse-width-modulation switching techniques. The solar charger additionally protects the batteries from deep discharge, disconnecting them when a low-voltage threshold is reached.

Given the power requirements of the experiments and devices used in this work, two 1293 x 329mm commercial silicon solar panels were used, together with two 12V lead acid batteries connected in series. The selected solar controller includes the adequate pre-programmed charging cycle for the batteries.

3.1.3 Mounting System Module

The system includes a weatherproof UV-stabilized enclosure to mount electronic components. It is installed on a tripod providing mechanical support to the complete system and physical storage space for MASS-related and external components. It offers connection with the exterior in order to interface with sensors and to receive solar power input.

A modified weather station enclosure was used in this work to benefit from its incorporated capacity to keep the components protected from sunlight, dust and moist. Built as a white fiberglass-reinforced enclosure it is designed to reflect the solar radiation, therefore maintaining a relatively moderate internal temperature when exposed to the sun. Modifications include a hinge-based second floor to provide additional space for electronic components, and also weatherproof ducts to

communicate with the exterior. The enclosure was mounted on a standard three meter-tall galvanized steel weather station tripod, as shown in Figure 3.2. Child experiment sensors are intended to be mounted on the top of the tripod in order to minimize external effects caused by factors such as people and shadows.

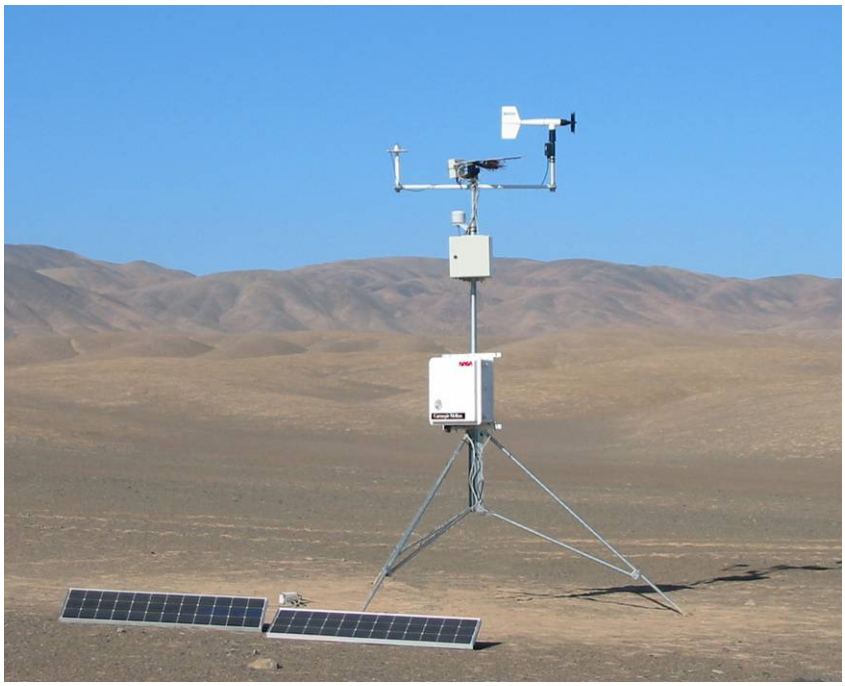

Figure 3.2: MASS / SCTU system installed in the field

3.1.4 Power Manager and User-Interface System Modules

The MASS includes a power manager system for power control and a user-interface system for user interaction. Although the two functions are not related, both systems are controlled from a single microcontroller that independently manages both units.

The user-interface includes an onboard mechanism for user control and monitoring. The device incorporates a small LCD screen to display an ordered menu-system, for the user to perform routine tasks over the MASS or child experiments without using external tools.

The power manager globally controls the power budget of the MASS by switching devices On only when they are required to operate, and switching the system Off if the battery voltage decreases below a configurable threshold. The complete powering-scheme is configured using the user-interface system.

The user-interface/power manager systems is a relatively large system involving several algorithms and specific components. The integrated system will be covered in detail in section 3.3.

3.2 Software Core

The software core defines the basic rules and programming code structure for all MASS-related *processes*[3] running on the main computer. All MASS and child software which directly or indirectly uses one or more of the MASS modules must follow these rules in their programming code.

The MASS includes a *core process* which manages the user interface / power manager module by handling user input and executing power schemes (details of the core process are covered in section 3.3.3). This is a crucial software for the operation of the MASS and must run at all times while the computer is powered. This process must be the only entity that directly communicates with the microcontroller.

In the case of child experiments, in general terms the main computer must run at least *n* independent processes for *n* implemented experiments. Frequently these processes need to communicate with other child processes to exchange relevant data (e.g.. configuration parameters) or with the core process to execute MASS-specific actions (e.g. external user requests). Methods such as the use of files or

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[3] A *process* is referred in this document as an entity capable of executing a given piece of code, that has its own execution stack, its own set of memory pages, its own file descriptors table and a unique process ID.

direct memory access to share information between processes are discarded because of speed limitations and sharing conflicts, among other potential problems. The software core states that inter-process communication must be achieved using System-V *IPC*[4] messages. Two or more processes can exchange information if they access a common system message queue. The *sending process* places a message onto a queue through a message-passing module. Then the *receiving process* accesses the same queue and retrieves the message. *Sending* and *receiving* processes need no synchronization between them, being able to read or write the queue at any given moment. A message in the queue will never interrupt the receiving process and will only be received when the queue is checked. As a consequence, if the sending process needs to be certain that the message was received, a two-way communication system with acknowledge and timeout must be programmed.

Running independent processes for each child experiment takes advantage of the multitasking capabilities of the Linux operating system and makes it possible to incorporate with ease new child experiments. Routines that were originally written independently from the MASS may be easily incorporated as a new process to the system, and only minor modifications are needed only when inter-process communication is required in order to implement IPC messaging.

Hardware conflicts caused by two processes accessing a single piece of hardware is also solved using IPC message requests. Only a single process directly accesses the device, receiving IPC message requests from other processes to execute actions on their behalf[5]. Therefore, in case several independent processes need to

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[4] Unix System V Release 4 was developed by AT&T Bell Laboratories, incorporating message queues for interprocess communication (IPC), among other functionalities such as shared memory and semaphores.

[5] This solution is analogue to the system used by the core process, where it is the only entity that directly communicates with the microcontroller.

access a single piece of hardware, a dedicated “server” process for the hardware is implemented. Then, this is the only process that directly communicates with the shared device, providing services to other processes through IPC messages to control the hardware. This implemented solution avoids the need of a synchronizing unit to handle hardware access.

The system developed in this work runs a single child process to handle the complete SCTU child experiment. This process controls several external components such as data logging systems and testing units and also communicates with the core process to exchange data with the user-interface system. The SCTU process is analyzed in detail in chapter 4.

3.3 Power Control and User-Interface Systems

Sections 3.3.1 and 3.3.2 presents specific characteristics of the power manager and user interface systems. Finally, sections 3.3.3 and 3.3.4 discusses all shared elements (microcontroller and operating software) of both systems.

3.3.1 Power Manager System

The MASS system is designed to operate continuously providing energy and services to child experiments at all times. As a solar-powered system, the daily amount of energy available is variable, and depends on the sun-power available and also in the size and efficiency of the power solar panels. Due to the existence of an uncertainty factor, the MASS tries to reduce the power consumption of devices whenever possible in order to prevent potential power outages[6].

The MASS is designed to use its components in an energy-efficient way in order to provide services to child experiments at any time of the day. Its ability to

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[6] The incorporation of higher capacity batteries or larger solar panels is discarded in order to keep a portable and reduced-sized system.

switch Off selected devices introduces important energy savings specially when high-consuming devices with short duty-cycles are switched Off (e.g. the pan/tilt unit in the SCTU). Additionally, it optionally incorporates the concept of “night operations” when no experiments and no user-monitoring are required during predefined times of the day. During these episodes it makes a controlled shutdown of the main computer of the MASS, reducing power consumption to the minimum and only switching it back On during “day operations”, when experiments are needed. Furthermore, the system incorporates continuous battery-state monitoring capabilities, performing a controlled shutdown of the computer when battery voltage levels drop below a user-defined threshold.

All components from the MASS and child experiments are grouped either as *devices that need permanent power* or *devices whose power supply can be interrupted*. Permanently-powered components should be extremely-low consumers with requirements that are negligible compared to the total capacity of the batteries of the system. Devices such as the microcontroller or weather loggers that need to capture data continually fall under this category. All other components, including most child experiments, must be considered as devices whose power must be controlled. Figure 3.3 shows a simplified power-scheme of devices whose power can be interrupted. As the experiments are assumed to be controlled by the main computer, direct power control from the microcontroller over the experiments is not required since the PC is the core of their execution. Therefore, the microcontroller only controls the power state of the computer.

Devices that need permanent power are fed using switching power supplies directly connected to the batteries. These regulators are characterized to be extremely efficient, guaranteeing that only a reduced amount of power will be lost in dc to dc voltage conversions.

Devices whose power is controlled by the microcontroller or by the PC are managed by opto-isolated solid-state relays (SSRs). Therefore, power control of high-consuming components is achieved by generating standard TTL digital control signals.

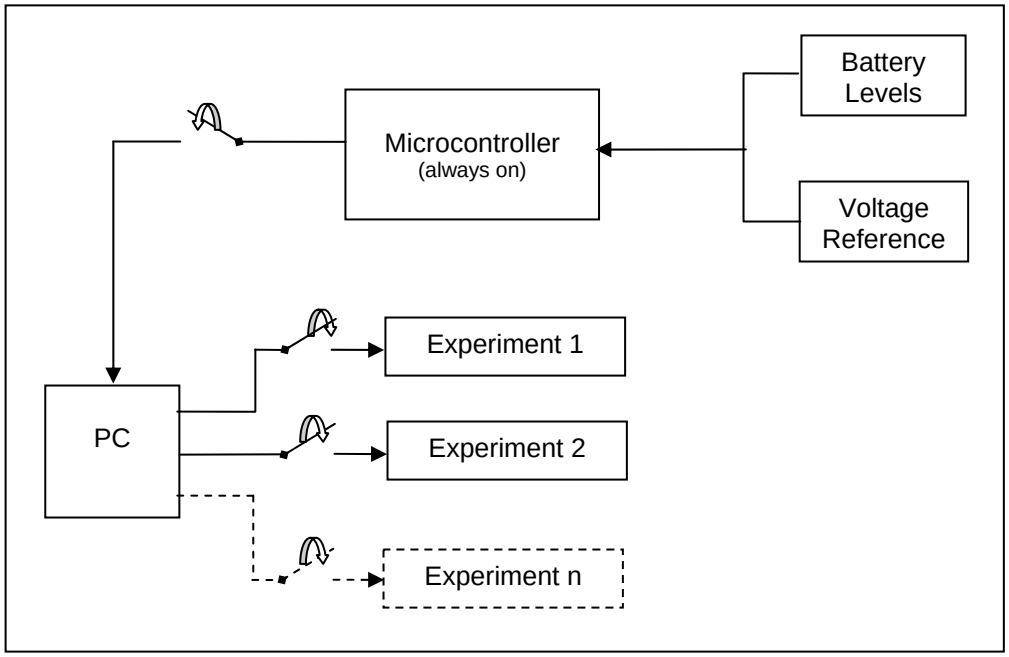

Figure 3.3: Simplified power-control diagram of devices whose power can be interrupted

3.3.2 User-Interface System

The user-interface system provides direct interaction capabilities between the user and the MASS by including a small alphanumeric display and keypad onboard. The user can execute actions on the MASS or can indirectly access any of the child experiments using IPC messages. Figure 3.4 shows the user interface system (keypad and user display) implemented for this work.

The user-interface is completely operated by the microcontroller and communicates with the core process of the MASS when needed. The device displays relevant data on the user display, receives user-input from the keypad and stores relevant execution values in its internal EEPROM memory. Additionally, the microcontroller may be indirectly used by child experiments (through the core

process) to store internal values, display local data on the user screen, and for the user to perform manual requests (e.g. data processing) on the experiment.

Figure 3.4: Implemented user interface system

Child-specific values may be stored in the EEPROM of the microcontroller to avoid recompilations during routine changes or calibration. These parameters can be modified using the user-interface even when the main computer is powered down. Therefore, all values can be updated without requiring external hardware (e.g. keyboard/monitor, external computer, etc) when operating in the field. To implement all this child-specific functionality in the microcontroller, its firmware must be updated[7].

The interface system includes menus with primary options and several submenus grouping related functions. Child-specific functions may be added as new options in existing groups or create complete new submenus. Navigation is achieved

[7] The firmware is written in a high-level programming language (C).

in an analogue way to cellular telephone systems with cyclic menus. Basic options of the MASS included in the user-interface are the following:

- Main Menu: It cyclically displays user-relevant data on the alphanumeric display, including status of the system (“online”, “permanent off”, “back in X minutes” during sleeping time, “system loading”, “system boot failure” or “lost connection”), battery voltage and relevant values of child experiments. This is the default state of the system when the interface has not been used in a predefined time.

- Power Manager Menu: Includes several submenus related to powering up and down the system. Basic submenus are the following:

  - *Turn the system permanently On or Off*. Starts or stops regular operations. When turned On, the system starts to monitor battery voltage and day/night operation times.

  - *Forced On*. Turns the system On with no experiments overriding “day” and “night” limits and low voltage conditions. This option allows the user to get data from the PC during night operations (when experiments are not needed), switching the computer momentarily On. This state must be manually executed to resume normal operations.

  - *Turn the system Off for “today”*. This option turns the system immediately Off, turning it back On “tomorrow” morning according to the predefined schedule. This function is useful when experiments are not required for the current conditions (e.g. bad weather) or when irradiance conditions are poor for battery charge, setting the system in a “charging state” to prevent emergency shutdowns in the future. Additionally, this option can be used to exit from the “*Forced On*” state engaging the scheduling system again.

- Configure Menu: Includes several submenus related to the storage of relevant parameters in the EEPROM memory of the microcontroller. Basic stored parameters are: low battery voltage threshold for turning the system Off, time

of the day when “night operations” start and total length (in minutes) of night operations.

The specific implemented menu system used for the MASS / SCTU in this work is exposed in Appendix G, including specific options for the SCTU child experiment.

3.3.3 User Interface & Power Manager Software: The Core Process

The core process running on the PC is crucial for the operation of the power manager and user-interface systems of the microcontroller. The core process acts as the coordinating unit between the microcontroller and the rest of the system, being the only process that directly communicates with it. It generates scheduled or emergency shutdowns, powers down devices that are not in use, provides child experiments with execution parameters stored in the microcontroller, publishes relevant user-values on the onboard display, and executes manual requests upon user request.

i) Scheduled Shutdowns

During scheduled shutdowns the core process generates an auto-shutdown procedure in order to save energy. These procedures are executed at predefined times of the day, relying on the microcontroller to be powered back On. The algorithm defines “day” and “night” operations, which are arbitrary times of the day defined by the user. During “night operations” no power-controlled experiments are executed and no external information is displayed on the user screen because the computer is powered-off. The PC is automatically turned back on by the microcontroller at the beginning of “day operations” according to a configurable time determined by the core process before the computer was halted.

ii) Emergency Shutdowns

Emergency shutdowns are also computer-generated halt requests, but they are a consequence of the detection of a potential power problem. The core process periodically receives scaled battery voltage[8] information from the microcontroller and generates an auto-shutdown procedure if its levels decrease below a configurable-threshold. This mechanism prevents a deep discharge of the batteries and an abrupt drop of power. When an emergency shutdown is generated, all day operations are cancelled until the following day. This allows the batteries to be recharged, avoiding endless-cycles of powering up and down due to voltage variations caused by variations in the system load.

Figure 3.5 summarizes the implemented algorithm for the execution of shutdown procedures.

iii) Configurable Thresholds

All decision parameters such as limits of night/day operations and voltage-thresholds are configurable values which are stored in the microcontroller to be used by the core process in the computer. This process polls for the stored values when needed according to the protocol detailed in Appendix F. Therefore, the user is able to dynamically update parameters using the user-interface, even when the computer has been powered down.

The implemented solution uses the advanced processing capacity of the computer to take all powering decisions, but taking advantage of the features offered by the user-interface as well. Therefore, the programming code must not be recompiled and there is no need to access files in the hard drive because all

[8] The scaled value is a reduced battery voltage that matches the ADC range of the microcontroller. It is expressed in internal microcontroller counts which is proportional to the real voltage value.

thresholds values are informed to the PC but not stored on it. Therefore all the complexity of the power manager system relies on the PC, and the PC only uses the microcontroller to perform simple user-interface tasks.

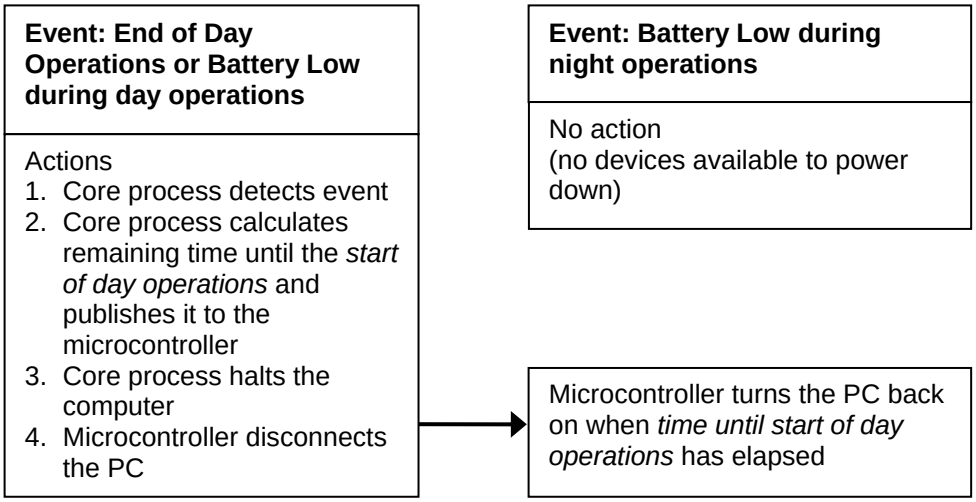
Event: End of Day Operations or Battery Low during day operations
Actions
1. Core process detects event
2. Core process calculates remaining time until the start of day operations and publishes it to the microcontroller
3. Core process halts the computer
4. Microcontroller disconnects the PC
Event: Battery Low during night operations
No action
(no devices available to power down)
Microcontroller turns the PC back on when time until start of day operations has elapsed

Figure 3.5: Summary of implemented algorithm to perform an automatic shutdown of the system

iv) Communication with the microcontroller

The core process periodically communicates with the microcontroller using a custom protocol designed for the MASS. The protocol is comprised of computer-generated synchronous messages and microcontroller-generated asynchronous messages. Only synchronous messages are acknowledged, where the microcontroller sends relevant parameters to the core process as an answer to the original message. Details of the protocol are described in Appendix F. A general description of the protocol is covered in section 3.3.4, subsection c).

3.3.4 Microcontroller

The microcontroller that manages the power manager and user-interface systems is a low-power device that operates continually, having power requirements that are negligible compared to the total capacity of the batteries. Due to its

extremely low power-consumption it should operate for weeks with the energy in the batteries even during low power episodes, due to its capacity to disconnect high-consuming devices before the battery voltage levels decrease to critical values.

For the power manager system, the microcontroller acts as a passive unit most of the time, acting only upon orders received from the core process of the computer. In the case of the user-interface, the system is autonomously executed allowing the user to navigate through an ordered-menu system and store relevant values without requiring additional processing capacity.

a) Voltage Monitoring

Voltage monitoring is executed by the microcontroller, which constantly reads the battery voltage using its internal analog to digital converter (ADC). The captured voltage is a scaled value of the real battery voltage that matches the range of the ADC. The scaled value is obtained from an adjustable high-impedance voltage divider (potentiometer).

The ADC uses an external voltage reference to perform the analog to digital conversion, thus minimizing erroneous readings such as those generated by a fluctuating power supply. The external reference is composed by a Zener diode and a potentiometer to adapt the breaking voltage of the diode.

b) Time Monitoring

The time monitoring system is used to measure time accurately while the main computer is down. Time measurement is needed in order to systematically switch On and Off the main computer at predefined times of the day. To achieve this precision requirement, an auxiliary low-frequency crystal clock was enabled in the microcontroller in addition to the high-frequency crystal used for the main clock. The low-frequency crystal overflows a counter in an exact number of seconds generating an interrupt, where precise time operations may be performed.

c) Firmware of the Microcontroller

The firmware of the microcontroller is one of the most relevant components of the MASS system, being the nucleus of the user-interface and power manager systems. The microcontroller achieves these tasks running a single routine based on interruptions.

Communication with the central computer is achieved through a standard RS/232 serial port from the microcontroller using the custom-built protocol described in Appendix F. A general overview of the protocol in the context of the hardware is shown in Figure 3.6.

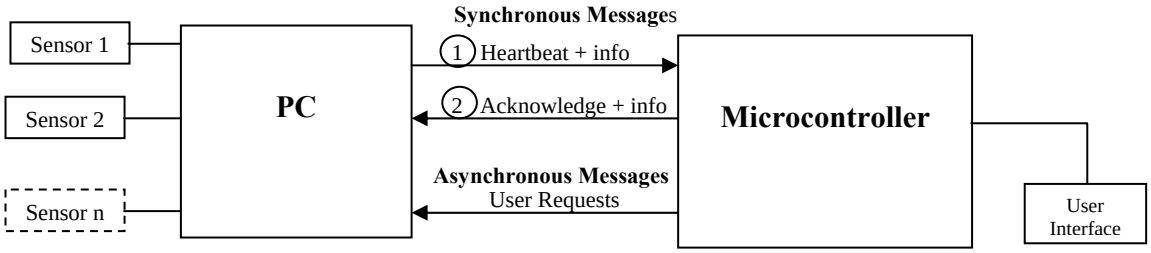

Figure 3.6: Basic block diagram of the communication protocol between the computer and the microcontroller in the hardware context

All synchronous messages are computer-generated requests directed to the microcontroller to perform relevant tasks (e.g. data to display on the user screen, power-down requests, etc). These messages also act as “heartbeats” (or “keep alive”) messages to the microcontroller, in order to confirm that the system is operating normally. Heartbeat messages must be received from the core process on a regular-basis, containing new or else redundant data if there is no new relevant information available. Lack of regular communications causes the microcontroller to assume communication problems and display a “lost connection” message on the user screen. All synchronous messages are answered with relevant data to the core process (e.g. battery voltage, answer to requests, etc).

In parallel, the user interface can generate microcontroller-transmitted asynchronous messages as a result of user requests. These messages are transferred to the core process when needed and they are not acknowledged.

4 SOLAR CELL TESTING UNIT (SCTU)

4.1 Objective

The objective of the Solar Cell Testing Unit (SCTU) is to accurately characterize solar cells when operating on the earth, providing tools for a comparative analysis between new and conventional photovoltaic technologies. The system makes an electrical characterization of the solar cells and provides data to determine other relevant parameters such as efficiency, fill factor, spectral response and temperature sensitivity, among others. Furthermore, the system can vary the orientation of the solar cells (fixed positions and sun-orientation) to quantify the benefits of a sun-tracking system and to analyze the influence of the incident radiation angle on the overall solar cell performance.

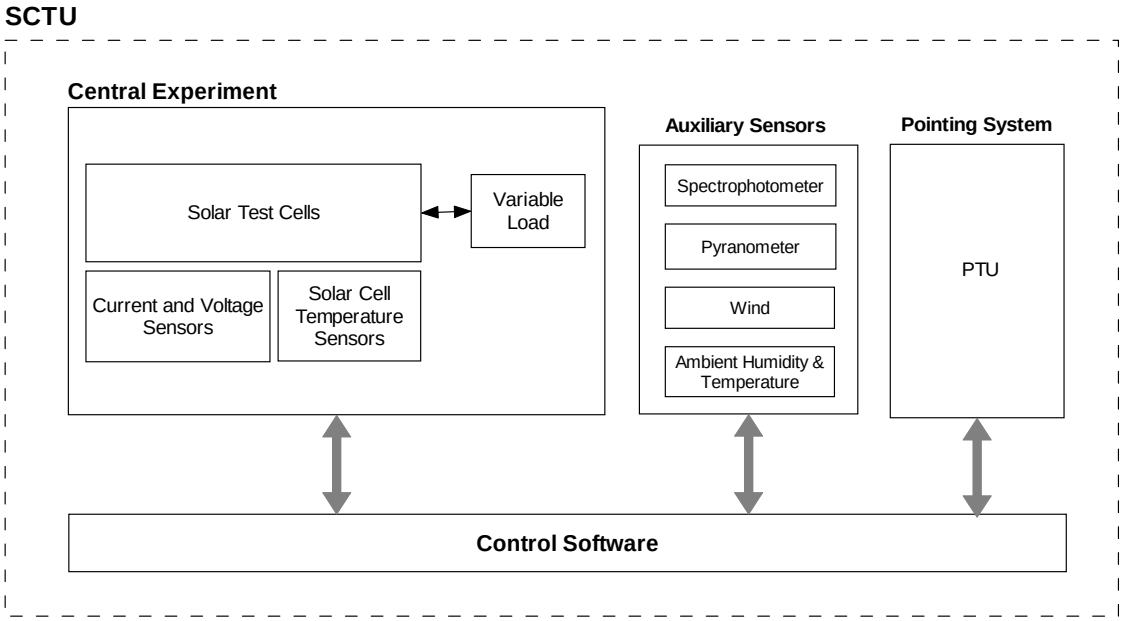

Figure 4.1 : General block-diagram of the SCTU system

4.2 Implemented Solution

Figure 4.1 shows a general block-diagram of the SCTU. The system is comprised of several units that perform specific independent tasks that aid the solar cell characterization. The “central experiment” performs direct tests to the tested solar cells, including an electrical characterization and solar cell temperature measurement; the “auxiliary sensors” provide complementary environmental data that affect the performance of these devices; the PTU (pan/tilt unit) allows to change the incident position of the solar cells; and the control software operates the complete system performing experiments, capturing sensor data and orienting the solar cells appropriately. The system is installed on the mounting system provided by the MASS (not shown in Figure 4.1), which is analyzed in section 4.2.4.

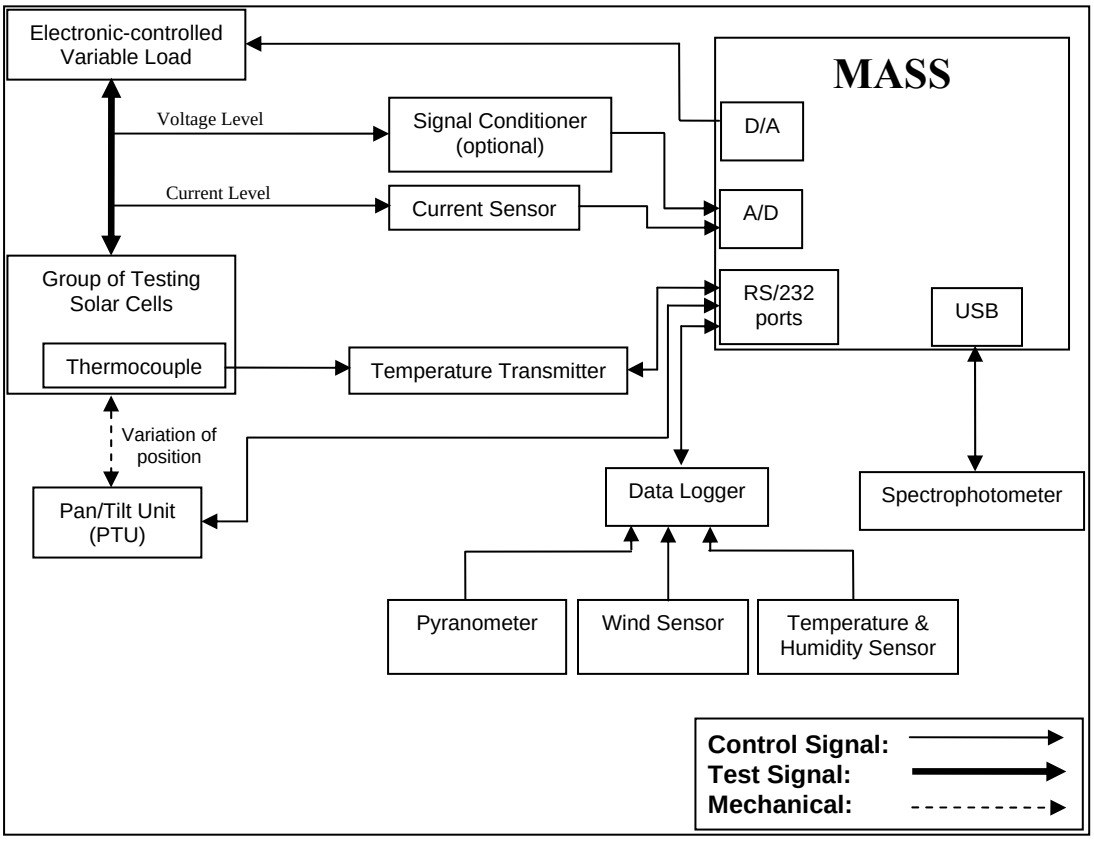

Figure 4.2: Block diagram of the SCTU and interaction with the MASS

Figure 4.2 shows an electrical block-diagram of the implemented SCTU interacting with the MASS (does not include interface with power manager and user-interface systems). Current and voltage signals are logged in the MASS after they have been conditioned to match its electrical input specifications (when needed). The SCTU is controlled by a "child experiment" process running on the main computer of the MASS. Auxiliary data is captured by a spectrophotometer and a general-purpose data logger.

4.2.1 Central Experiment

As mentioned above, the central experiment performs direct tests to the solar cells, including an electrical characterization and measurement of the solar cell temperature. The electrical characterization determines current-voltage (I-V) curves under variations of its load in incremental steps. These curves are characteristic to the specific solar cell technology used.

The implemented system allows to test two independent sets of solar cells which are analyzed on a consecutive basis. The same load and current/voltage sensors are switched to the appropriate solar cell set when performing tests. Therefore comparative results are obtained because both experiments are performed under equivalent conditions. The system developed in this work includes a set of silicon solar cells (conventional technology) and a set of the newly commercially-available Advanced Triple Junction (ATJ) n/p InGaP/InGaAs/Ge solar cells, traditionally used on satellites.

A general implementation scheme of the system is shown in Figure 4.3.

a) Load control

A single electronically-controlled load is connected to the set of solar cells to be tested. The device acts as a current regulator, forcing the current to be proportional to a voltage signal controlled by the MASS. If the solar panels cannot deliver the demanded current, the load acts as a short-circuit. The control software must be appropriately designed so that the variable load covers the complete range of

operation of the specific solar cells used, including sufficient resolution points to generate complete I-V curves (open-circuit to short-circuit).

As the SCTU is designed to characterize two different sets of solar cells under equivalent electrical conditions, the variable-load is switched to connect to the appropriate testing solar panel using a switching relay. This relay is indirectly controlled by a digital output of the MASS through a solid-state opto-relay.

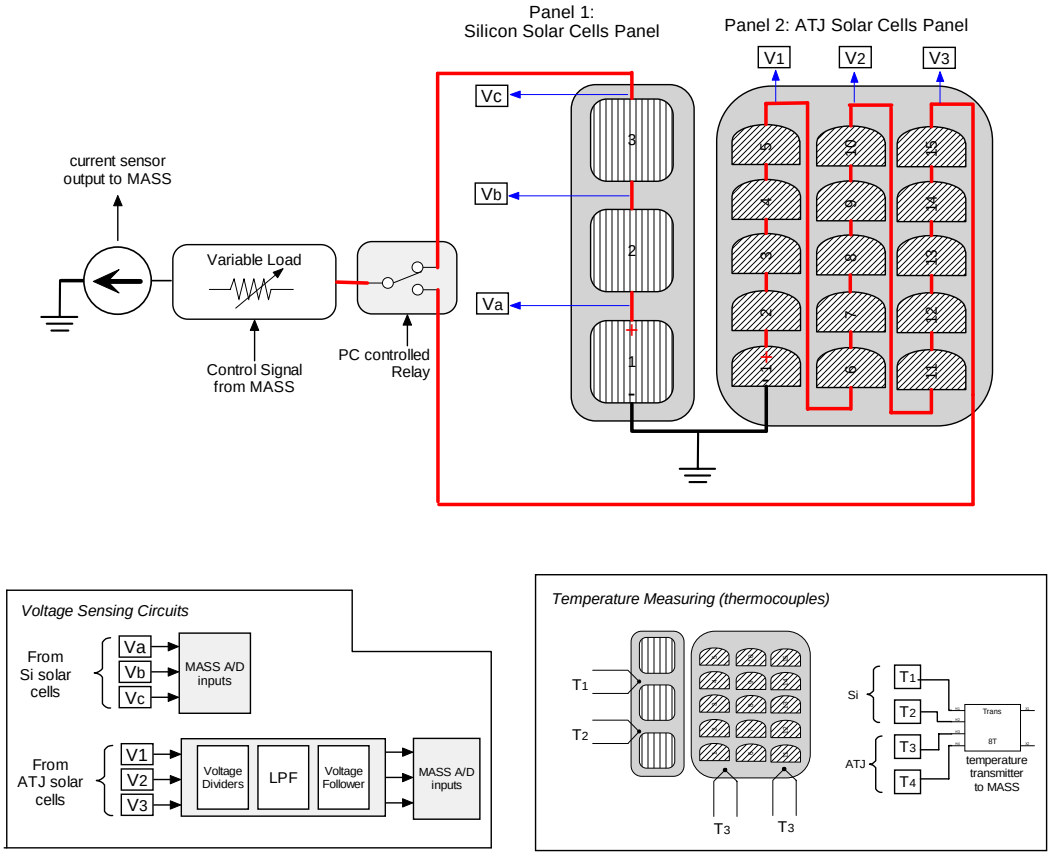

Figure 4.3: Block diagram of the Central Experiment

b) Current Measurement

Current measurements of the solar cells are performed using a magneto-resistive current sensor whose operation is based on the anisotropic magneto-resistive (AMR) effect. The output of the sensor is a voltage proportional to the measured current. The output voltage range meets the electrical standards of the analog input of the MASS so it can be directly connected to that system.

Electrically, the current sensor is connected in series with the variable load (see Figure 4.3), being switched by the same relay connecting both solar cell sets. Therefore, a single sensor for current measurement is used, allowing to get comparable current measurements and thus avoiding potential differences between sensors.

c) Voltage Measurement

The voltage measurement electrical implementation is specific for the particular set of solar cells that are being tested, which is dependant on the expected history-maximum output voltage of the solar cells. Sensed voltages should never exceed the electrical limits of the A/D converter of the MASS. Higher-expected voltages occur during high-irradiance episodes during open-circuit conditions.

In the case of the silicon solar cell sets used, the open-circuit voltages will never exceed the maximum voltage accepted by the analog input of the MASS. Due to its low impedance, the voltage signal is directly connected to the analog input of the MASS.

Conversely, ATJ solar cells are expected to operate at higher voltages and lower currents than silicon solar cells due to its construction characteristics. Open-circuit voltages regularly exceed the maximum voltage limit allowed by the analog input of the MASS. In order to decrease this input voltage a high-impedance voltage divider is implemented, obtaining a scaled value with negligible power losses. This high-impedance voltage divider exceeds the maximum input impedance recommended for the analog input of the MASS. Therefore, a voltage follower is also included in order to decrease the input impedance observed by the MASS.

Additionally, a low-pass active filter was also incorporated to remove eventual electric noise in the signal. Voltage divider, low-pass filter and voltage follower are grouped and built together in a “signal conditioner” board.

d) Solar Cell Temperature

Each set of solar cells includes two K-type thermocouples located in two different locations of the solar panel as seen in Figure 4.4 for the ATJ solar panel (location is analogous for the silicon solar panel). To determine the temperature of the solar cell sets, a temperature transmitter to interface with the thermocouples is used. The transmitter is programmed to operate with the specific kind of thermocouple providing a calibrated output temperature upon request from the central computer of the MASS. The device digitally transmits the temperature values from the four thermocouples.

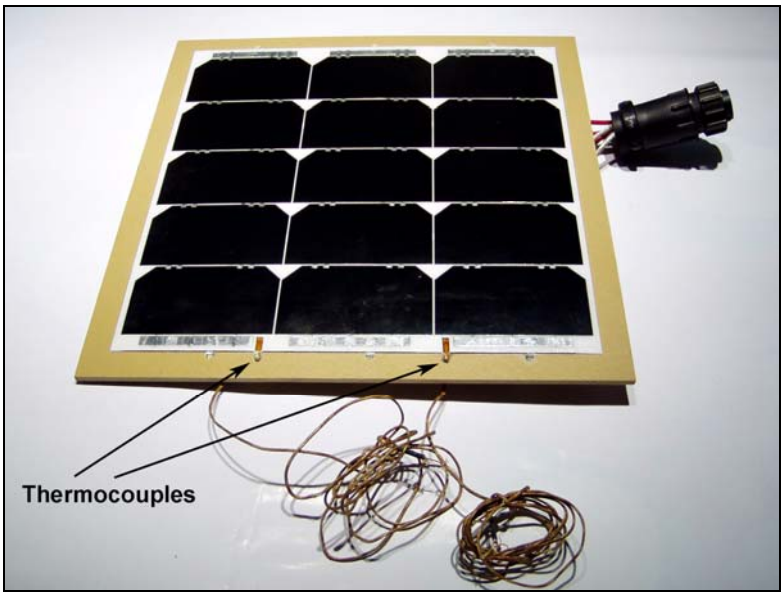

Figure 4.4: ATJ solar cell set used in the SCTU (embedded thermocouples are shown)

4.2.2 Pointing System

The objective of the pointing system is to characterize testing solar cells under different external conditions. The solar cells and complementary instruments are mounted on a pan/tilt unit (PTU) that can vary its orientation from horizontal to sun-pointing or any fixed orientation at any given moment (a picture of the mobile platform is shown in Figure 4.5). This mechanism provides the tools to quantify the power benefits of implementing a sun-tracking system for applications such as robots. It may be additionally used to determine the influence of the incident sun-angle over the efficiency of the solar cells due to reflections and varying path-lengths on each semiconductor caused by changes in the angle of the incident light.

Figure 4.5: SCTU mobile platform pointing to the sun

The main component of the solar-tracking system is its operation software. Sun position is analytically determined knowing the geographical location (latitude and longitude), and day and time of the year. This has economic advantages over sun-locating sensors, but requires precision when installing the device in order to get proper orientation.

Sun-tracking software uses the SPICE[9] library written by NASA. SPICE system is used as the mechanism for capturing, archiving and disseminating a variety of ancillary and engineering information needed by scientists involved in mission design, observation planning, science data analysis and visualization, and correlation of data between multiple instruments. SPICE ancillary data includes spacecraft trajectory, target body ephemerides, target size/shape/orientation, spacecraft orientation, instrument mounting and field-of-view geometry, and commands and events associated with the conduct of a mission. By providing SPICE with the current geographic location and current date and time, the SCTU is able to get the position of the sun at any given moment.

The implemented system in this document uses a commercial PTU device based on a stepper motor. The pan/tilt unit includes a PTU controller which is operated using a standard RS/232 serial line of the MASS. The PTU has a freedom of 300º pan, 46º tilt (bottom) and 31º tilt (top). The pan range allows to track the sun during daylight, but the tilt range may be a limiting factor on certain locations during specific times of the day. The SCTU was built to operate in the latitudes ranging from the Atacama desert to Rancagua, Chile, where the sun is positioned in the range of the PTU during all the relevant high-irradiance times of the day for the complete year.

The selected PTU is a big power consumer, what is mainly caused by the controller servoing the PTU to maintain the desired position. Therefore, the PTU was integrated to the power manager system of the MASS, only being powered during experiment execution when repositioning of the solar cells is required. Powering of the device is achieved using an opto-relay SSR controlled by the main computer of

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[9] SPICE is the standard for nearly all NASA planetary missions such as Galileo, Clementine, MGS, Mars Odyssey, Cassini, NEAR, DS-1, Stardust, MER, Deep Impact, MRO and CONTOUR. It will also be used on Mars Express (in parallel with ESA standards), and it could be used on ESA's Rosetta, Japan's Nozomi, or other foreign missions.

the MASS, as discussed in section 3.3.1. Dramatic power savings are introduced by the power manager when no experiments are performed (e.g. after sunset). Although the selected PTU requires initialization procedures to determine its absolute position each time it is powered, it was empirically determined that better power efficiencies are obtained with numerous initializations on a day rather than continuous powering.

4.2.3 Auxiliary Sensors

The main objective of the auxiliary sensors is to capture data that characterizes the incident environment affecting the solar cell performance for the analysis of results. All data is periodically captured and retransmitted for logging in the MASS. Onboard measurements include solar spectrum, irradiance (total power per area), environmental temperature, relative humidity and wind speed. The described system is implemented using a general-purpose data logger which is operated through a RS/232 serial line from the MASS and a spectrophotometer operated through USB.

a) General-purpose data logger

The general-purpose data logger is a programmable device able to interface with an enormous variety of sensors for different purposes. Its interface offers analog inputs, pulse counters, switched voltage excitations and digital ports. The system runs user-programs (built with a proprietary programming language), being able to scan measurements at independent intervals and make more complex operations such as averaging of measurements and raw data conversion to units. It offers data storage capabilities, being capable of operating for long periods of time without communication with the MASS. It logs the data from the pyranometer, wind sensor and temperature / relative humidity sensor, periodically transferring data to the MASS during “day operations”. New sensors may be easily incorporated by modifying its internal user-program.

The general-purpose data logger is an extremely-low power consumer (negligible compared to the total capacity of the batteries), so the system is powered directly from the batteries of the MASS with no power control. Therefore the system continually logs data from its sensors, even during night operations. This allows to

permanently log weather variables even when the MASS is powered down, allowing to characterize the surrounding environment. Deep-discharge of the battery is unlikely to occur because, according to electrical specifications, they should provide the data logger with enough power for days, even when the MASS was powered down due to low voltage conditions.

Table 4.1 shows the main electrical characteristics of sensors used by the SCTU that are connected to the general-purpose data logger.

Table 4.1: Main characteristics of the SCTU sensors connected to the general-purpose data logger

Sensor	Main Characteristics
Pyranometer	-Flat spectral response for the full solar spectrum -Spectral Response Waveband: 305 – 2800nm -Maximum Irradiance: 2000 W/m^2 -Operating Temperature: -40 to 80ºC
Wind Monitor	-Measures wind speed & direction - Range of operation (speed): 0 – 60 m/s -Accuracy (speed): 0.3m/s -Range of operation (direction): 355º (electrical) -Accuracy (direction): 3º
Temperature & Relative Humidity Sensor	-Temperature Range: -40ºC to 60ºC - Expected error: < 0.6ºC for 0-35ºC range -Relative Humidity Range: 0 to 100% - Typical long-term stability: <1% RH per year

b) Spectrophotometer

The spectrophotometer allows to analyze the performance of the solar cell sets, capturing the incident solar spectrum. The device is mounted on the same mobile-plate of the testing solar cells (controlled by the PTU) in order to capture the exact incident solar radiation of the panels.

The spectrophotometer was incorporated mainly to analyze the performance of ATJ solar cells when comparing results to existing studies in space. ATJ solar cells are constructed including three junctions in series optimized to capture specific parts of the spectrum. If the atmosphere eventually filters relevant wavelengths to one of the junctions, the performance of the whole solar cell may be degraded due to its serial configuration. Therefore, spectral differences in space and in the atmosphere may be used to analyze the obtained results.

The system developed for this work uses a spectrophotometer which is powered and operated through a USB interface. It uses a closed proprietary communication protocol so its operation is restricted to the software provided by the manufacturer. It has two independent channels (master and slave) which together cover a spectral range from 200 to 1100nm. Although the spectrometer does not cover the complete spectral range used by ATJ solar cells (300 to 1900nm, approximately), it includes the part with the highest irradiances (visible region).

4.2.4 Physical Layout

All devices related to the SCTU are installed using the mounting system module provided by the MASS. Sensors and solar cells for testing are mounted on the PTU located on the top of the MASS tripod (see Figure 4.6). Most of the electronics within the SCTU, including the signal conditioner board, PTU controller and general-purpose data logger are mounted in the MASS electronics enclosure. A SCTU-specific secondary electronics enclosure was installed on top of the tripod in order to place the variable load as close as possible to the test solar cells. This minimizes cable length requirements of the solar cell/variable load circuit, minimizing undesired inductive noise and resistive losses.

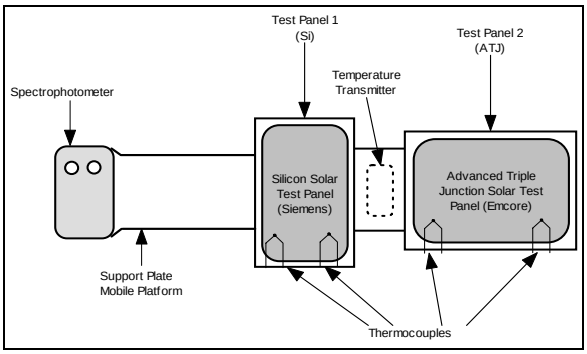

Figure 4.6: Top-view diagram of the mechanical layout of SCTU mobile platform

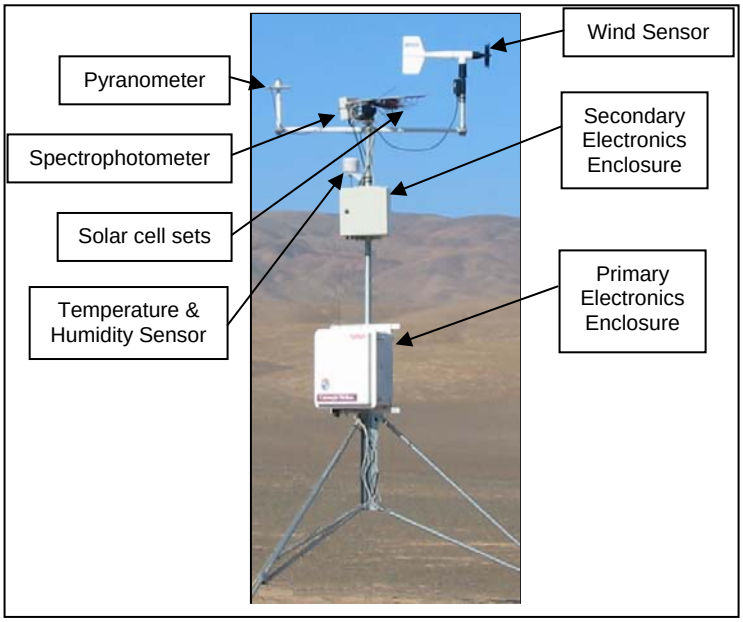

Figure 4.7: Main components of the MASS/SCTU mounted in the field

Figure 4.7 shows the mounting scheme of the SCTU devices. Figure 4.8 shows the layout of components of the SCTU in the primary and secondary electronics enclosure.

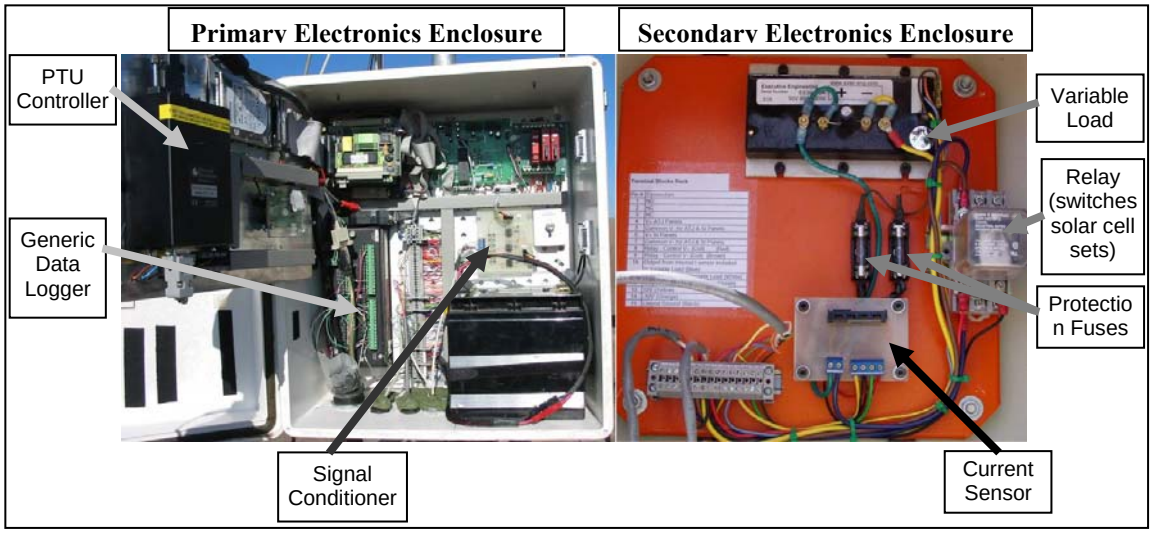

Figure 4.8: Layout of components in the Primary and Secondary Electronics Enclosure

4.2.5 Control Software

The SCTU is operated by a single independent process running on the main computer of the MASS. It operates the general-purpose data logger, temperature transmitter, PTU controller and central experiment using the features of the MASS. The process uses RS/232 serial interfaces for communications, digital outputs to switch to the appropriate solar-cell set and to power down the PTU when not in use, analog outputs to operate the variable load and analog inputs to read current and voltage levels. It additionally communicates with the core process of the MASS to receive user-generated orders, calibration parameters and powering down

requests. It generates ordered logs with captured data and generates Octave[10]-formatted scripts to create plots that need to be generated on a regular basis.

All instruments of the SCTU are operated on a sequential-basis to prevent sharing conflicts on the main computer of the MASS. Therefore, only one Interrupt Request (IRQ) line is used to operate all RS/232 serial devices (data logger, temperature transmitter and PTU), minimizing hardware occupation.

a) General Operation of the software

The child process runs a loop which periodically executes a set of experiments, logging current, voltage and temperature data for the complete range of operation of each set of solar cells in every predefined position. Predefined positions are flat-panel, sun-pointing and any other desired fixed position defined by the user. Therefore, during each loop the software powers-up the PTU, points the mobile platform to the first predefined position and controls the variable-load to operate the first set of solar cells from open-circuit to short-circuit. Once it has finished, it switches the load to the second set of solar cells and repeats the experiment. The PTU is sequentially pointed to each of the following predefined positions, repeating equivalent experiments for each orientation for both solar cell sets. A summary of this procedure is shown in Figure 4.9. Once finished, the PTU is finally powered-down until the next set of experiments is performed.

[10] Octave is a free software written under the terms of the GNU General Public License (GPL) by John W. Eaton and others. The software is a high-level language, primarily intended for numerical computations with capabilities similar to Mathworks Matlab®.

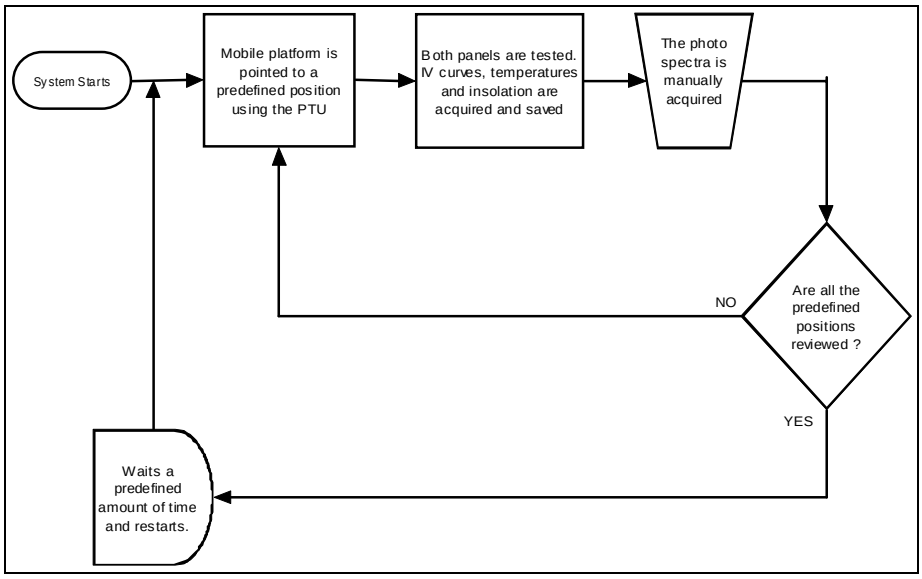
System Starts
Mobile platform is pointed to a predefined position using the PTU
Both panels are tested. IV curves, temperatures and insolation are acquired and saved
The photo spectra is manually acquired
Are all the predefined positions reviewed ?
NO
YES
Waits a predefined amount of time and restarts.

Figure 4.9: Flowchart of the general software operation

Part of the power manager execution of the MASS is performed in the child experiment, powering up and down the PTU. This is done for simplicity purposes since the child process is the only program requiring to control the power of the PTU. Alternatively, control of power could have been integrated to the rest of the power manager, being controlled by the core process and receiving powering requests from the child experiment through IPC messages. This solution was avoided because it introduces additional complexity to the system without major benefits.

b) Integration with the MASS

The SCTU takes advantage of the features of the MASS designed for child experiments. Relevant configuration parameters that are subject to frequent changes are stored in the EEPROM memory of the microcontroller, including geographical location (latitude and longitude) and correction values for the PTU orientation. Additionally, the user can generate manual commands through the user-interface, including sun-pointing at any moment and the suspension of the solar-cell experiment (therefore only logging weather data, acting as a weather station). The user can also read the latest weather data available on the user-display according to the current data logged by the process of the SCTU. All functionality offered by the

MASS is achieved by communicating with the core process of the MASS via IPC messages, as described on earlier sections.

c) Software of the electronically-controlled load

As discussed in section 4.2.1 in order to control the variable load a voltage control-signal must be generated in incremental steps in order to vary the solar cell operation from open-circuit to short-circuit. This is achieved by the SCTU using the D/A converter of the MASS. The process logs only data points that provide valuable information, i.e. points which are obtained until the short-circuit condition is reached[11]. The control range used for each set of solar cells (from open-circuit to short-circuit) is empirically determined for the specific set of solar cells that are being tested. These parameters must be introduced in the programming code of the process. As a consequence in the implemented SCTU, silicon and ATJ solar cell sets have dedicated connectors that cannot be interchanged. Furthermore, the programming code will need modifications (and recompilation) if new solar cell sets with different electrical characteristics were incorporated to the system.

d) Data processing

The SCTU process incorporates data processing of the logged data, ordering captured information. Data is ordered on a daily-basis, generating separate files and directories for each day of experiments. Weather data is logged in an independent text-file each day, incorporating data from all weather sensors in a single file. Solar-cell electrical data is logged in independent daily-created directories, storing in them all the multiple files[12] generated during each experiment

[11] As the variable operates controlling current the short-circuit condition is dependant on the characteristics of the solar cells used.

[12] Each experiment of a particular set of solar cells pointing in a particular direction generates an independent text-file log.

execution. All logs, including weather data and solar-cell data are tabulated text-files that can be directly imported by Octave or Matlab software.

Furthermore, the SCTU process automatically generates Octave plot scripts that generate commonly-used graphs on a daily-basis. Generated plots include weather graphs, the current-voltage curve (highlighting the maximum power point), and any other custom relevant variable defined by the user. Weather plots are generated with one day of delay, generating scripts for the previous day when the SCTU process is ran for the first time on the day (this is when the complete data for the previous day becomes available).

e) Auxiliary process for manual operation

The software of the SCTU includes an auxiliary (and optional) process (independent from the main process of the SCTU previously described) in order to manually operate the SCTU devices. This auxiliary process must be manually executed by the user by logging into the main computer of the MASS directly or through network access. Once the process is executed the user gains direct control over the SCTU, being able to point the solar cells at arbitrary positions and to execute experiments at any given moment. This manual execution is useful when the user wants to perform the experiments at precise intervals with particular external conditions, and to take external manual measurements such as the spectrum for certain precise orientations.

In order to prevent sharing conflicts between the main SCTU and auxiliary processes only the primary process directly accesses the hardware of the SCTU. The auxiliary process generates requests which are received by the main process using IPC messages, executing actions upon request. IPC messages used for communication between the main and auxiliary processes constitute an independent queue that has no relation with IPC communication between the core process of the MASS and the rest of the child processes.

In order to interrupt the execution of automatic solar cell experiments during manual operations, the auxiliary process generates an IPC flag upon execution. Once this flag is set, the main SCTU process only operates under requests

from the auxiliary process until this flag is removed when the process is exited. Therefore, it is important to exit the auxiliary process properly, by using the included interface in order to remove the execution flag and resume automatic operations.

f) Implemented MASS / SCTU processes

Figure 4.10 shows a general block-scheme describing the main tasks performed by the running process of the MASS and SCTU systems. Inter-process communication and hardware management of external devices are also included. Blocks shown within individual processes only describe actions of the process and do not necessarily constitute the exact structure of the programming code. Blocks within the same process may achieve intercommunication that is not shown in Figure 4.10, implementing them as individual or common programming-functions of the process.

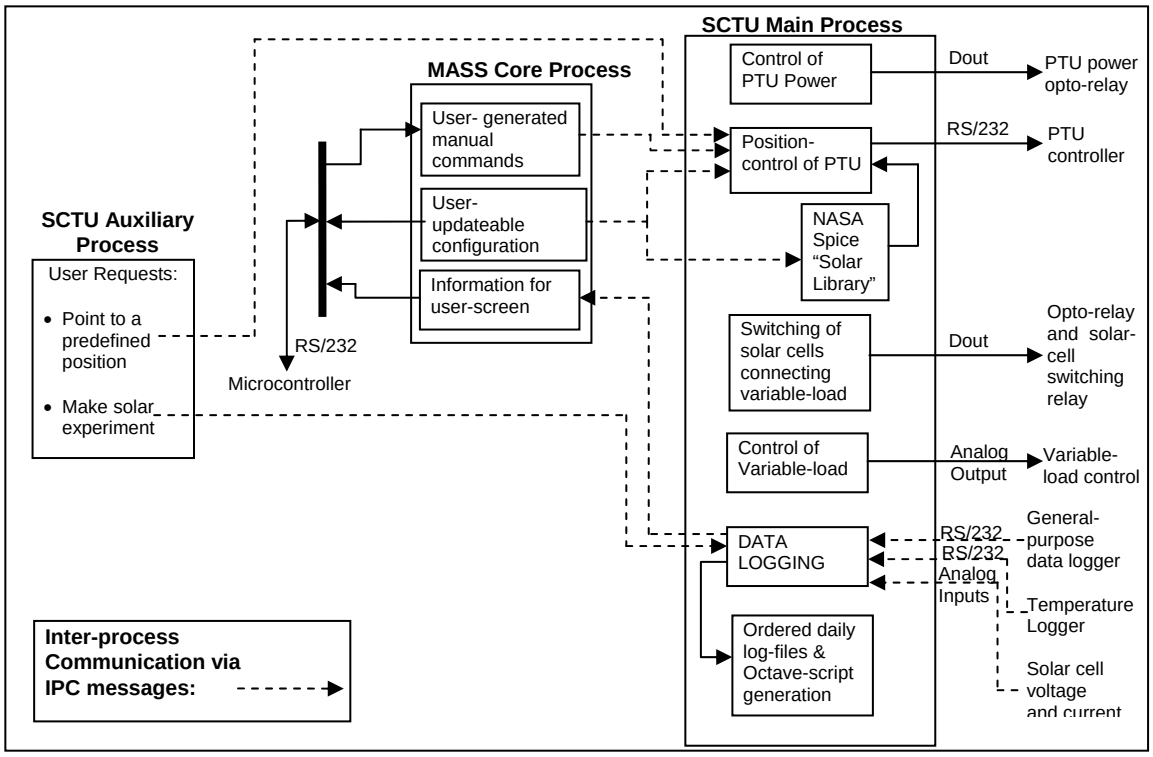

Figure 4.10: Block diagram of processes and main functions running by the MASS and SCTU in the main computer

5 RESULTS

In order to demonstrate the capabilities of the system and validate the quality of its data, the results of several automatically-executed experiments are presented. This section is only a brief summary of results obtained during the solar cell analysis and should not be used by themselves as concluding evidence about the performance of the tested solar cells.

Section 5.1 shows solar cell characterization results. This includes I-V curves for the ATJ and silicon solar cell sets, and I-V curve variation for ATJ solar cells along a single day. In addition, results of spectral measurements are illustrated. Finally, section 5.2 shows examples of automatically-generated weather plots created by the MASS with SCTU data.

5.1 Solar Cell Characterization

Experiments shown in this section were acquired during a single testing day on December 12, 2004 in the region of Rancagua (Chile). The selected day was a “typical” summer day on the area, sunny and completely cloudless.

5.1.1 Current-Voltage (I-V) Curves

One of the most distinctive characteristics of individual solar cell technologies is their current-voltage (I-V) curve. This curve is obtained by varying the load in incremental steps, constantly logging voltage and current values from open-circuit to short-circuit conditions, as described in earlier sections.

Figure 5.1 contrasts the characteristic curves of ATJ and silicon solar cells during the maximum irradiance episode of the day in horizontal position, showing relevant electrical parameters. Results confirm that both solar technologies operate in distinct electrical ranges and present significant differences in performance. Regarding data quality, captured I-V data from both solar cell sets lack of significant noise and are suitable for solar cell analysis.

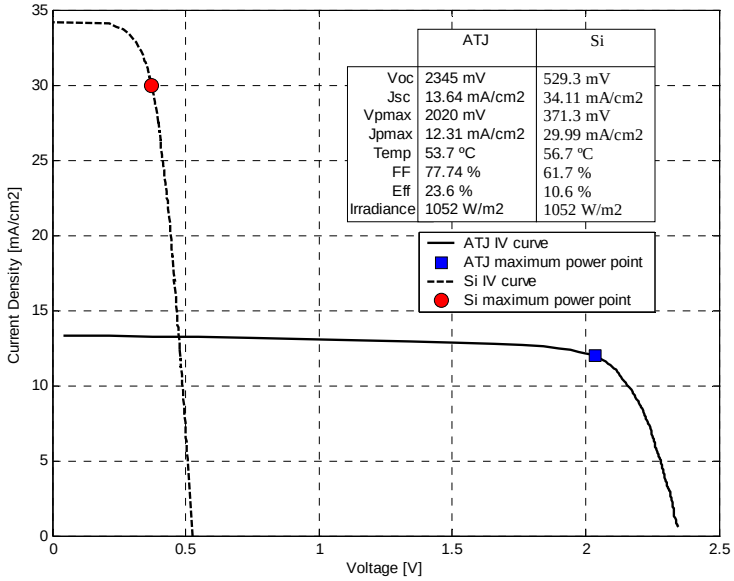

Figure 5.1: I-V curve for ATJ and silicon solar cells during the maximum irradiance episode of the testing day

ATJ solar cells operate at a higher voltage and lower current levels than silicon solar cells. ATJ technology demonstrates a noticeably higher conversion efficiency[13] than silicon solar cells, obtaining a 23.6% compared to the 10.6% of the silicon technology. While the ATJ curve has a more squared shape (sharp corner), the silicon curve is rounder, what is reflected on a higher fill factor (FF) of the ATJ technology.

[13] The conversion efficiency parameter indicates the percentage of incident solar power that the solar cell converts into electrical power.

5.1.2 I-V Curves during Different Times of the Day

The I-V curves presented in section 5.1.1 only reflect the performance of the solar cells during a particular instant of the day. I-V curves vary significantly during the day mainly because of variations in the sun radiation angle (cosine effect), influence of the atmosphere (changes in the relative position of the earth respect to the sun) and variations in solar cell temperature.

Varying curves during the testing day for the horizontal position are shown in Figure 5.2. ATJ and silicon technologies maintain significant differences in their electrical operating ranges. Variations of I-V curves along the day for each individual technology are mainly observed in the current values, being the open-circuit voltage almost stationary along the day.

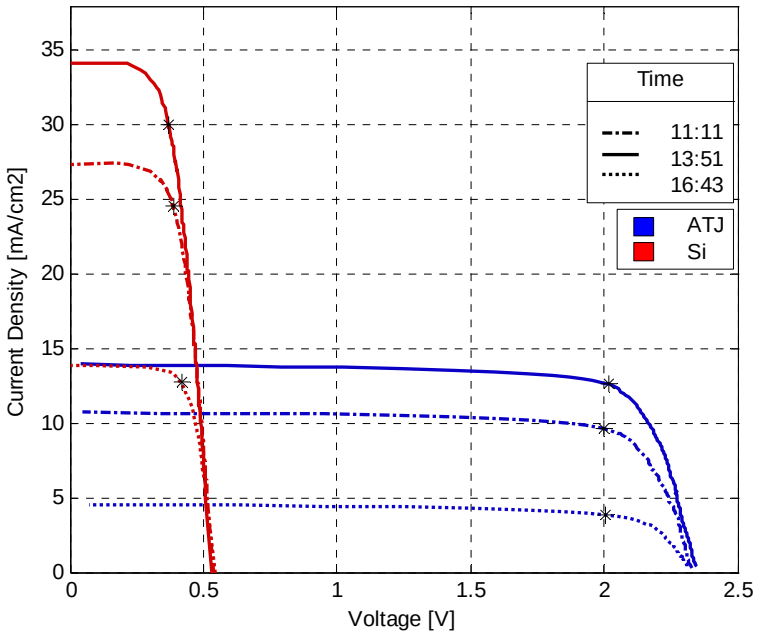

Figure 5.2: I-V curves of ATJ and silicon solar cells in horizontal position during the testing day. Maximum power points are marked with an asterisk (*)

As stated above, an important cause for curve changes during the day is the variation of the sun incident radiation angle, which is explained by the *cosine effect*. This effect states that for a surface located on a fixed position on earth the amount of incident sunrays will vary along the day due to variations of the exposed area to the solar rays[14]. The maximum amount of incident radiation on the fixed surface will occur when the incident sunrays strike perpendicular to the fixed surface. This occurs because during these episodes the parallel incident sunrays "see" the largest surface.

Changes during the day are also caused by the atmosphere, because the path length of the incident radiation varies with the position of the sun. Normal incident sunrays to the surface of the earth cross a smaller section of the atmosphere resulting in less attenuation. Conversely, when the path of the sunrays is largest, the attenuating effect of the atmosphere on the sunrays increases resulting in a lower irradiance. These path length differences may also cause variations in the solar spectrum, since the atmosphere can unequally filter certain wavelengths.

Furthermore, changes are also caused by variations in the temperature of the solar cell. Varying I-V curves may be corrected by temperature to make appropriate comparisons between experiments. Correction parameters are provided by the manufacturer or can be determined by empirical analysis. Correction by temperature is beyond the scope of this simplified analysis, but the expected behavior is of a higher electrical performance with lower operating temperatures.

5.1.3 Sun-tracking system

Figure 5.3 illustrates I-V curves for both technologies, which was obtained continually pointing the solar cells to the sun with the automatic sun-

[14] This approach considers that all the incident light to the surface is due to direct normal irradiance (beam irradiance), neglecting the influence of diffuse radiation (reflections of scattering).

tracking system of the SCTU. During these experiments the cosine effect is cancelled since the incident sunrays are normal to the solar cells at all times. Therefore, observed changes along the day are attributed mainly by path variations of the incident sunlight through the atmosphere and changes in the operating temperatures of the solar cells. An important improvement in performance can be observed related to Figure 5.2, specially during times of the day where the sun is far from the normal position (when the cosine effect degradation is stronger).

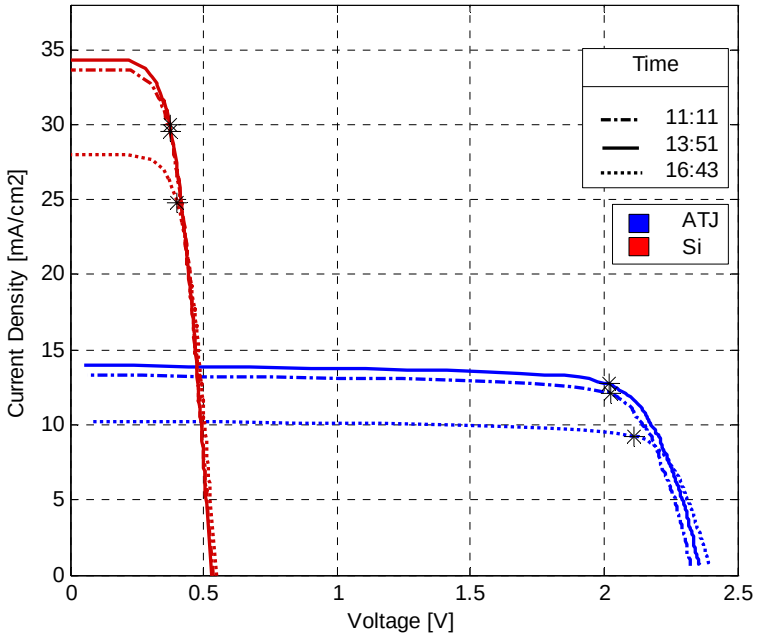

Figure 5.3: I-V curves for the solar cells pointing to the sun along the day. Maximum power points are marked by an asterisk (*)

5.1.4 Solar Spectrum Measurements

The spectrum of the incident radiation is crucial for the analysis of solar cells. Solar cell performance is dependant on the presence of specific bands of the spectrum, so its values are an important performance variable to consider in the analysis.

The spectrophotometer used by the SCTU generates a text file with the number of counts for each wavelength slot. This data must be corrected and calibrated obtaining the power density versus wavelength and area ($\frac{W}{nm \cdot m^2}$). The device includes two channels, the Master Channel covering the UV and visible ranges and the Slave channel covering the near-infrared segment.

Several spectral measurements were performed during the testing day. Figure 5.4 shows two solar spectra measurements (corrected and calibrated) at different times of the day in horizontal position. The obtained curve is similar to theoretical expected values, observing the maximum power per wavelengths near the maximum insolation episode. No important local differences besides amplitude can be distinguished between measurements along the day.

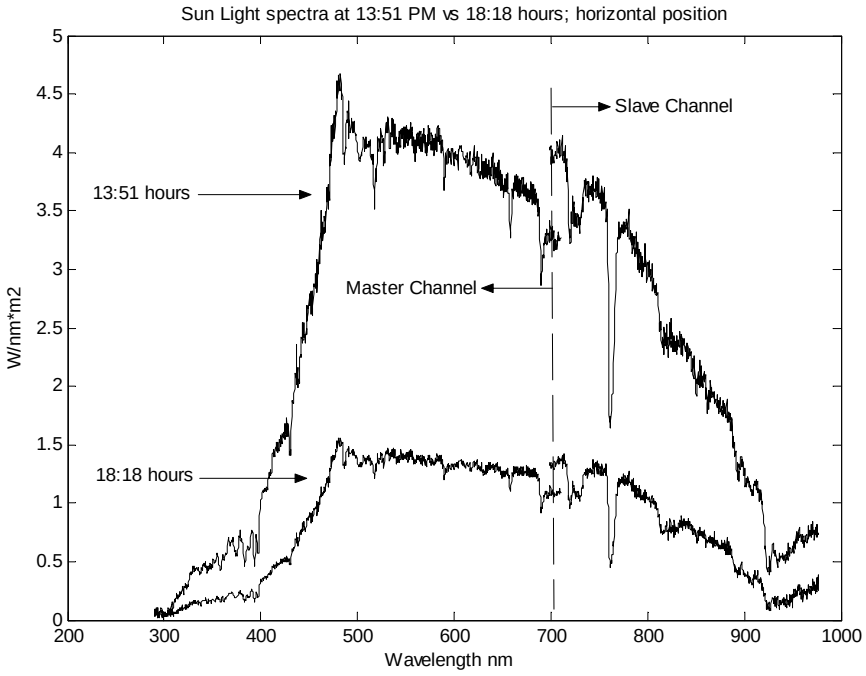

Figure 5.4: Sunlight spectrum during different times of the day

5.2 Weather Reports

As earlier discussed, the SCTU generates daily weather plots from sensors, logging the environmental temperature/humidity, wind speed/direction, and total solar irradiance. This section shows automatically-generated plots with the system installed in “Mina El Guanaco” in the Atacama desert (Chile) on October 18, 2004.

Obtained values are shown in Figure 5.5, Figure 5.6 and Figure 5.7. They appear concordant to expected values (contour and magnitude) and lack of significant noise. Therefore, these values are suitable for solar cell and environmental characterization considering that the instruments have been calibrated by the manufacturer.

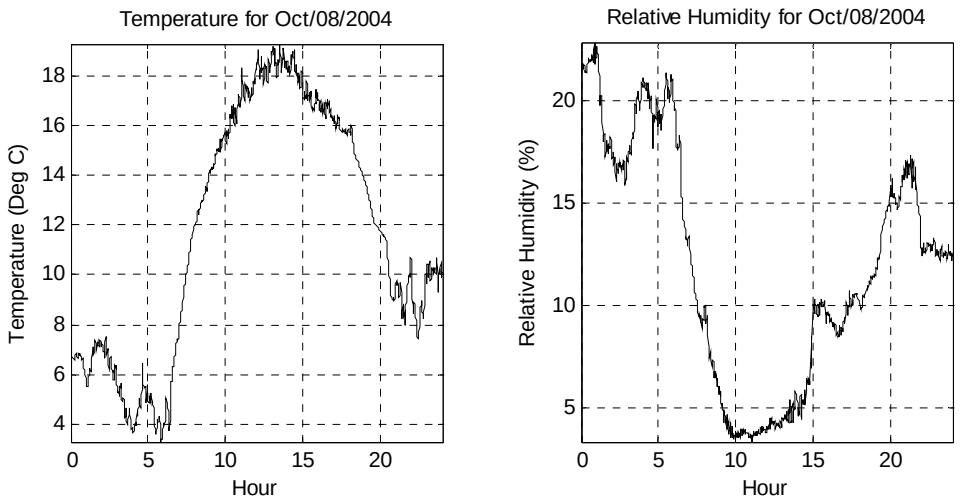

Figure 5.5: Temperature & Humidity weather plots

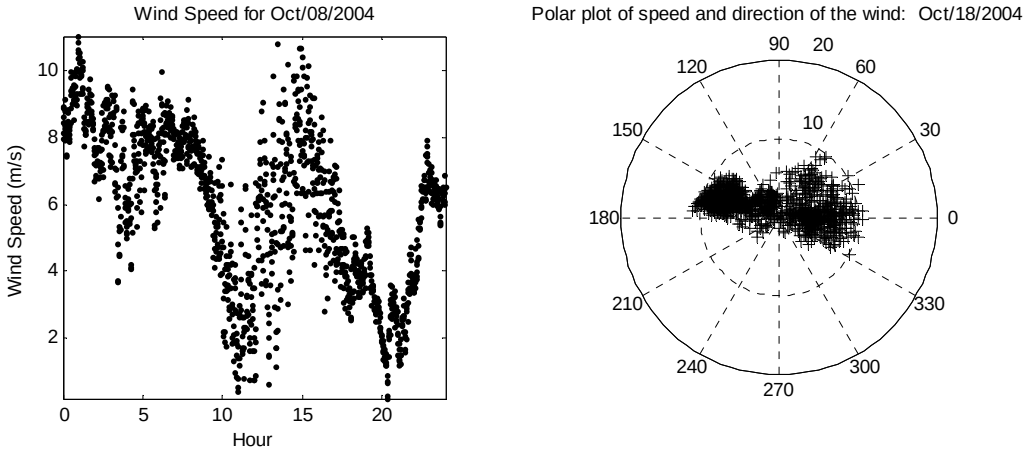

Figure 5.6: Wind Speed & Direction weather plots

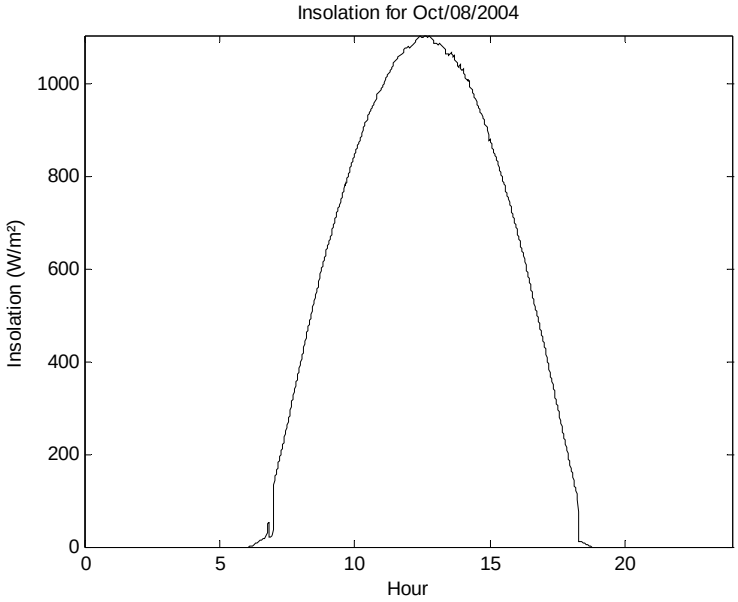

Figure 5.7: Solar Irradiance weather plot

6 CONCLUSIONS

This document has proposed solutions to address the difficulties of performing experiments in isolation requiring external support. The proposed system controls a solar cell testing unit that allows to characterize Advanced Triple Junction (ATJ) n/p InGaP/InGaAs/Ge solar cells built for space applications on the earth, in comparison to conventional silicon solar cell technologies. The proposed solution allows to get a sets of data for solar cell characterization under a variety of external conditions including results that are relevant for both, the electrical performance and mechanical/weather requirements of the solar panels.

Two prototype versions of the system have been successfully tested during field operations of the “Life in the Atacama” project of Carnegie Mellon University in the Atacama desert in Chile. They have been operated for two independent one-month periods with successful results. The final version of the system has been tested in the area of Rancagua, Chile capturing relevant data for an uninterrupted two-month period. The system has been completed to operate uninterruptedly during the three-month long field operations of “Life in the Atacama” during year 2005.

This document has intended to cover all technical details of the implemented solution serving the purpose of a technical manual, but also has intended to propose generic solutions to common problems of devices needing to operate autonomously and unattended. The development of a power manager system is proposed, providing hardware and software tools to minimize the power consumption of experiments that are performed in isolation. Additionally, a generic and expandable user-interface is proposed automating commonly user-required tasks that allow to perform these actions without requiring additional hardware tools.

Future work in the system shown in this document is completely opened to serve multiple purposes, from being just an autonomous weather station incorporating additional relevant sensors (precipitation, barometric pressure and leaf wetness, among others) to incorporating completely new child system using the MASS to receive complete support.

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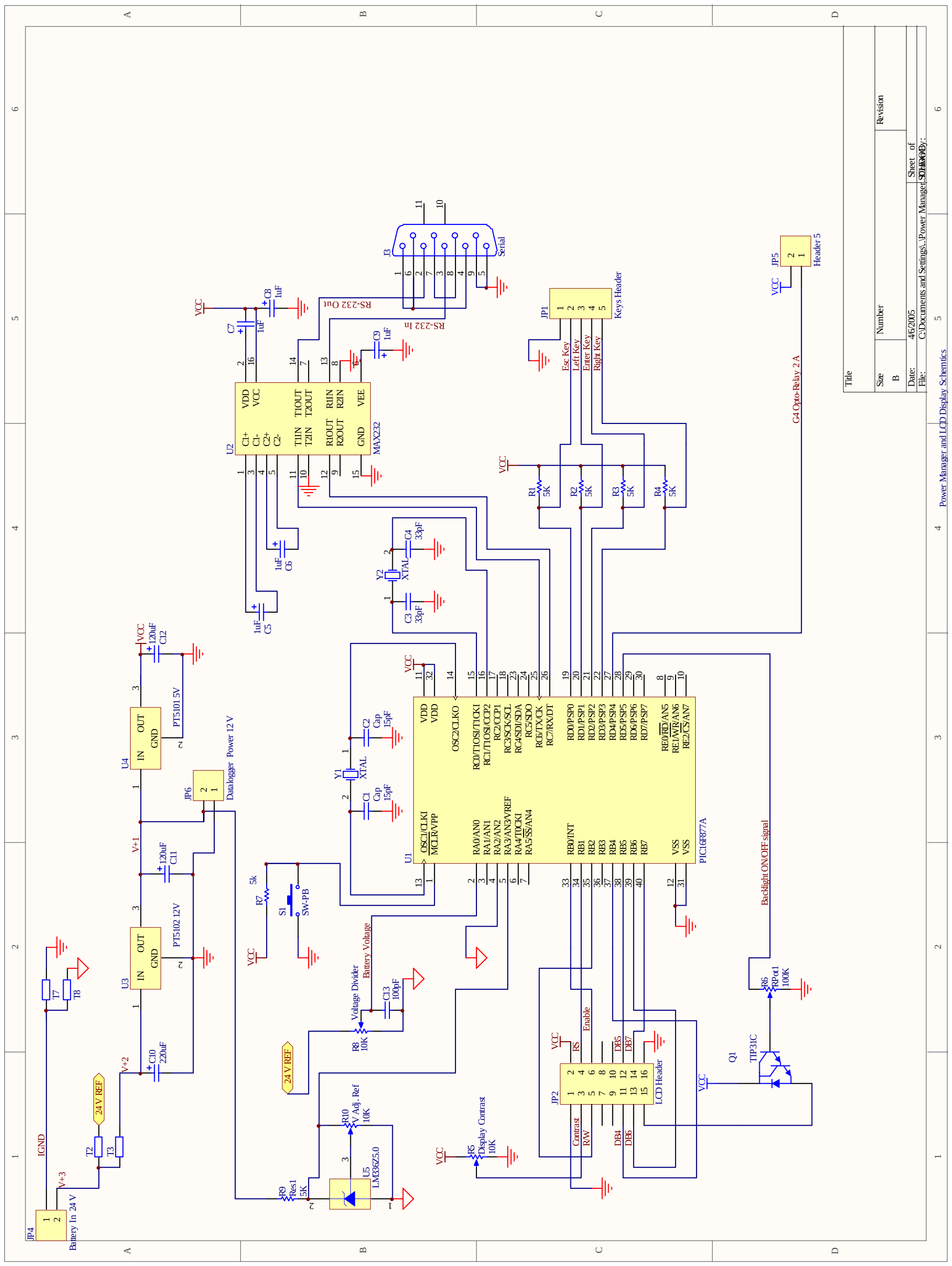
APPENDIXES

APPENDIX A ELECTRICAL DESIGN AND DETAIL OF DEVICES USED IN THE MASS

A.1 Schematic of Power Manager / User-interface Board



U1
PIC16F877A
OSC1/CLKI
MCLR/VPP
OSC2/CLKO
VDD
VSS
RA0/AN0
RA1/AN1
RA2/AN2
RA3/AN3/VREF
RA4/T0CKI
RA5/SS/AN4
RB0/INT
RB1
RB2
RB3
RB4
RB5
RB6
RB7
RC0/T1OSI/T1CKI
RC1/T1OSI/CCP2
RC2/CCP1
RC3/SCK/SCL
RC4/SDI/SDA
RC5/SDO
RC6/TX/CK
RC7/RX/DT
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RD1/PSP1
RD2/PSP2
RD3/PSP3
RD4/PSP4
RD5/PSP5
RD6/PSP6
RD7/PSP7
RE0/RD/AN5
RE1/WR/AN6
RE2/CS/AN7
U2
MAX232
C1+
C1-
C2+
C2-
T1IN
T2IN
R1OUT
R2OUT
GND
VDD
VCC
T1OUT
T2OUT
R1IN
R2IN
VEE
J3
Serial
RS-232 Out
RS-232 In
JP1
Keys Header
Esc Key
Left Key
Enter Key
Right Key
R1 5K
R2 5K
R3 5K
R4 5K
JP5
Header 5
G4 Opto-Relay 2 A
Y1 XTAL
Y2 XTAL
C1 Cap 15pF
C2 Cap 15pF
C3 33pF
C4 33pF
C5 1uF
C6 1uF
C7 1uF
C8 1uF
C9 1uF
U4
PT5101 5V
IN
OUT
GND
C12 120uF
JP6
Datalogger Power 12 V
V+1
C11 120uF
U3
PT5102 12V
C10 220uF
V+2
V+3
IGND
T7
T8
T2
T3
24 V REF
JP4
Battery In 24 V
R7 5k
S1
SW-PB
Voltage Divider
Battery Voltage
C13 100pF
R8 10K
R10
V Adj. Ref
10K
U5
LM336Z5.0
R9 Res1 5K
R5
Display Contrast
10K
JP2
LCD Header
Contrast
R/W
RS
Enable
DB4
DB5
DB6
DB7
Q1
TIP31C
R6
RPot1
100K
Backlight ON/OFF signal
VCC
Title
Size
B
Number
Revision
Date:
4/6/2005
Sheet of
File:
Drawn By:
Power Manager and LCD Display Schematics

Figure A.1: Schematic of Power Manager / User-interface Board

A.2 Connectors in Power Manager / User-interface Board

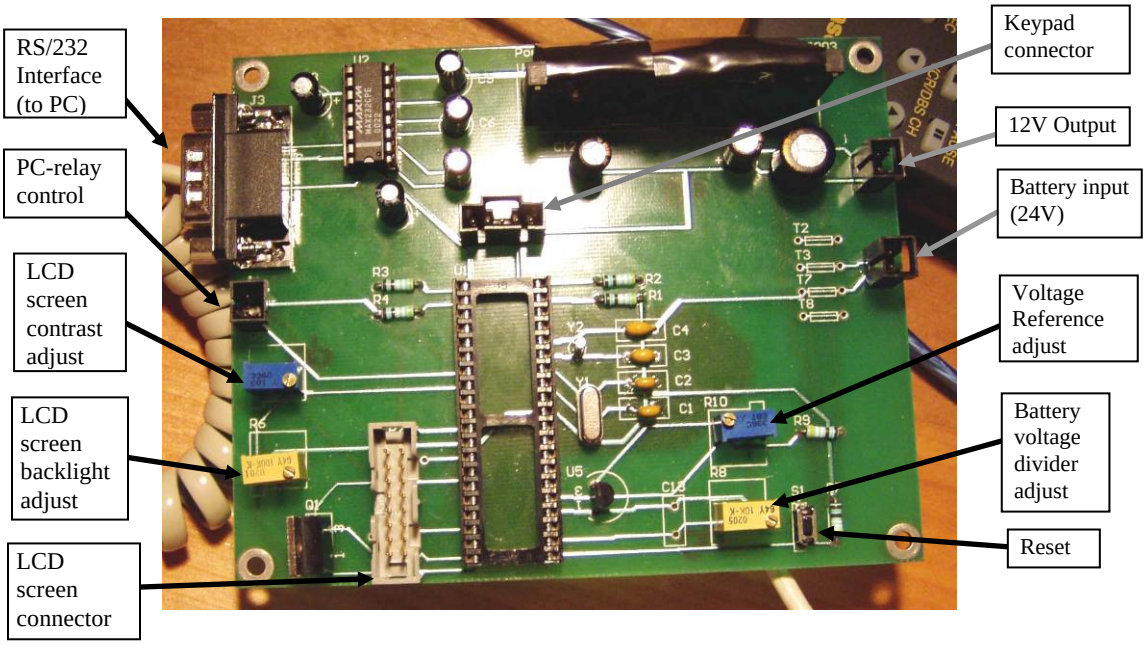

Figure A.2: Interface connectors in Power Manager / User-interface Board

A.3 Microcontroller: Battery Voltage Measuring System

The Power Manager system uses the analog to digital converter from the PIC microcontroller to read the battery voltage value, as described in the main section of this document. The PC shutdowns itself if the read voltage decreases below a threshold defined by the user. The microcontroller reads a raw voltage value between 0 and 1024[1], value which is proportional to the input voltage. The value in

[1] The analog to digital conversion is based on 10 bits. Therefore, $2^{10} = 1024$ discrete levels can be read by the microcontroller.

volts can be determined knowing the exact voltage of the Zener-reference (adjustable using a potentiometer on the power manager board) and the resistor values of the voltage divider (used to match the battery voltage to the voltage operation levels of the microcontroller).

The core process of the MASS in the main computer reads the raw voltage value obtained by the microcontroller and converts it to volts. The value in volts in retransmitted back to the microcontroller as text (according to the protocol shown in Appendix F) to be shown to the user on the LCD display. Although this system reduces processing requirements to the microcontroller, the user-interface is not able to show a value in volts when the system loses the processing power of the main computer of the MASS (night operations and low battery-voltage operations). As an alternative, during these operation conditions the user-interface shows the raw-voltage value on the user screen in the format “X/1024”, where X is the raw voltage. During night operations and low-voltage battery conditions the system is assumed to be unmonitored and battery voltage should not be needed by the user on regular operations. Anyway, during these conditions the user can alternatively read the battery-voltage from the included display of the solar controller.

A.4 Commercial Hardware used in the MASS System

Table A.1: Commercial hardware used in the MASS

Block	Device	Main Characteristics
Batteries	2 x Panasonic valve-regulated lead acid batteries Model: LC-X1220P	Nominal voltage: 12V (each) Nominal voltage: 20Ah (each) Note: both batteries are connected in series in the MASS
PC/104 stack	Main CPU Board: Kontron model MOPSlcd7	▪ Pentium III Processor ▪ 256Mb RAM ▪ 2 serial ports ▪ 1 parallel port ▪ USB ▪ 10/100 Base-TX Ethernet ▪ Onboard VGA interface
	Analog/Digital – Digital/Analog Board: Diamond Model MM-32-AT	Analog Inputs: ▪ 32 single-ended, 16 differential or 16SE+8DI o Current configuration: 32 single-ended inputs ▪ 16 bits A/D resolution ▪ Bipolar or unipolar, ±10V maximum detectable input, several input ranges ▪ **Maximum recommended impedance to input: 200Ω** Analog Outputs: 4 channels, 12 bit-resolution, several ranges available (maximum output: 10V) Digital I/O: 24 programmable I/O Other features: 2x 32-bit down counter, 1x 16-bit down counter, Clock: 10Mhz (internal) or external input
	Serial Board: Connect Tech Inc Xtreme/104	Board provides 8 additional serial ports. RS/232 and RS/422 (or RS/485) interfaces are available (jumper-selectable)

	Power Board TRI-M Model HE104	50W output 6V to 40V Input Range 5V, 12V, -12V regulated output
	Hard Drive:	Hitachi Travelstar 40GB Model: IC25N040ATCS05-0
Solar Panels for Power	2 x Siemens SM55 solar modules	36 single-crystalline Silicon solar cells per panel Weatherproof Maximum Power Rating: 55W (AM1.5, 1000W/m^2) Short Circuit Current: 3.45A Open-circuit voltage: 21.7V Bypass diodes for shading conditions Dimensions: 1293 x 329 mm
Solar Controller	Morningstar Corporation Prostar 15	▪ Charges batteries obtaining energy from solar panels ▪ Uses PWM techniques to operate solar panels in their maximum power point ▪ Supports different ranges of batteries and voltages ▪ 100% solid state ▪ Remote battery sense terminals ▪ Several electronic protections: short circuit, overload, reverse current at night, high voltage disconnect, high temperature disconnect, lighting and transient surge protection, among others ▪ LCD display and LED to show status, voltages and faults

A.5 Main Electronic components used in the Power Manager / User-interface Board

Table A.2: Electronic components used in the Power Manager / User-interface board

Block	Device	Main Characteristics
Microcontroller	PIC16F877	High performance RISC CPU, CMOS-FLASH-based 8-bit microcontroller 256 Bytes of EEPROM data memory; 368 bytes of data memory (RAM) 8 channels of 10-bit Analog-to-Digital (A/D) converter Interrupt capabilities Universal Synchronous Asynchronous Receiver Transmitter (USART/SCI) with 9-bit address detection 2 additional timers
User display	DMC-16202NY-LY-AGE	LCD Display 16x2 with Backlight
User keypad	Storm GS040203	4-key keypad Polymer casing keytops with configurable keytop graphics
Voltage Regulation	Texas Instruments PT5101 (5V) and PT5102 (12V)	1-A Positive Step-down Integrated Switching Regulator 90%+ efficiency Laser-trimmed output voltage Output current limiting Thermal shutdown protection Input voltage range: ▪ 9-38V (PT5101) ▪ 16-38V (PT5102) Output current: 0.1 – 1A

APPENDIX B ELECTRICAL DESIGN AND DETAIL OF DEVICES OF THE SCTU SYSTEM

B.1 General Schematic of the Solar Cell Testing Unit (SCTU)

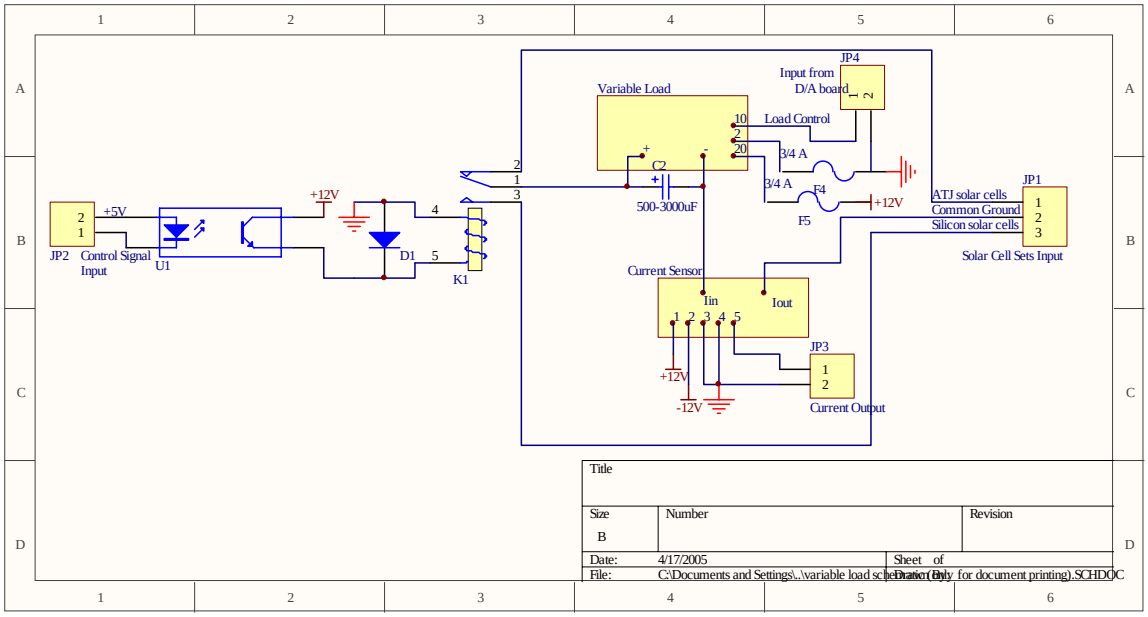

Figure B.3: Schematic of the SCTU system

Figure B.3 shows the schematic used to control the electronic-controlled variable load from the MASS. The diagram does not include details of the voltage monitoring signals, which connect directly to the analog to digital converter of the MASS in the case of the silicon solar cells, and through the signal conditioner board (shown in Figure B.7) in the case of ATJ solar cells.

Different components shown in Figure B.3 are distributed between the primary and secondary electronic enclosures. The electronic-controlled variable load, current sensor and switching relay are located in the secondary electronics enclosure in order to maintain cables connecting the testing solar cells and variable load the

shortest possible. The opto- isolator and voltage and current monitor signals are located in the main electronic enclosure interfacing with the MASS.

B.2 Connectors in Signal Conditioner Board

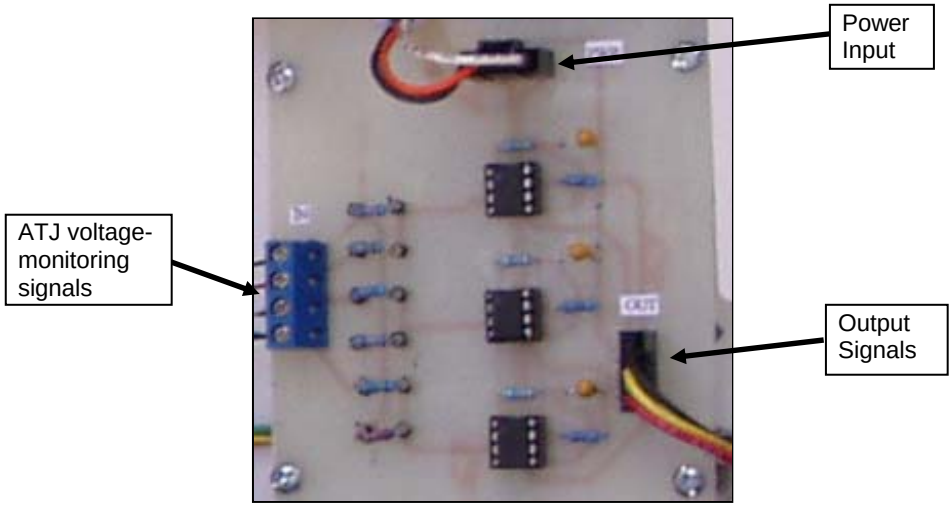

Figure B.4: Main connector in Signal Conditioner Board

B.3 Interconnection of Solar Cells for Testing

The ATJ solar cell set is built interconnecting in series fifteen Emcore Advanced Triple Junction solar cells. The solar panel is arranged in three rows of five solar cells each. Each row of solar cells provides a voltage output to monitor the voltage of each individual row. The three voltage outputs are logged by the SCTU system through the analog to digital board of the main computer of the MASS. Figure B.5 shows the connection scheme of the ATJ solar cell set.

The silicon solar cell set is built interconnecting in series three Siemens single-crystal silicon solar cells. Each individual solar cells provides an output to monitor the voltage of the individual cell. The three voltage outputs are logged by

the SCTU system through the analog to digital board of the main computer of the MASS. Figure B.6 shows the connection scheme of the silicon solar cell set.

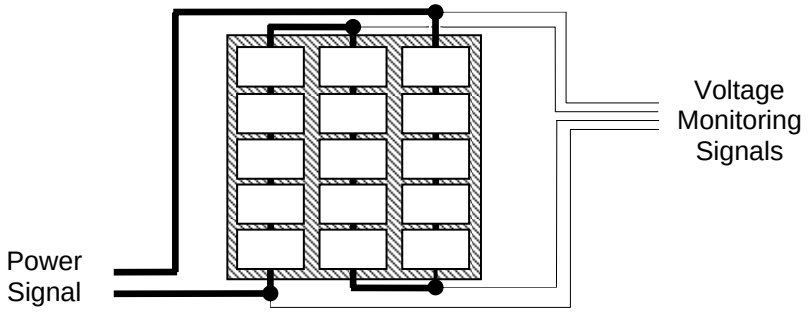

Figure B.5: Connection scheme of ATJ solar cell set used in the SCTU system

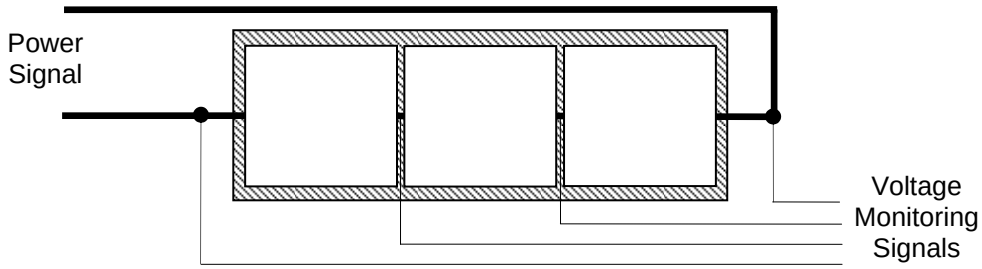

Figure B.6: Connection scheme of silicon solar cell set used in the SCTU system

B.4 Schematic of Signal Conditioner Board

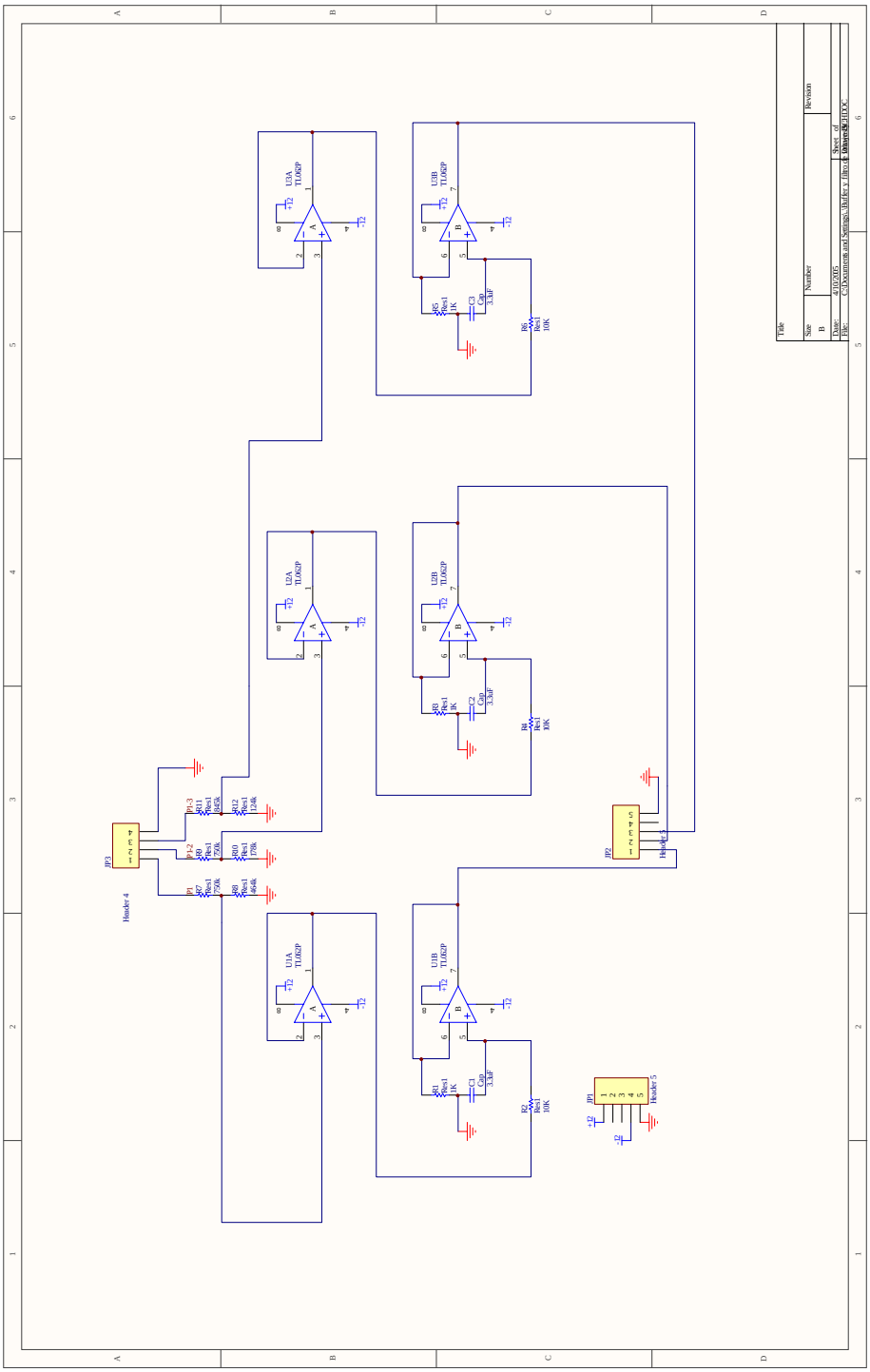

Figure B.7: Schematic of Signal Conditioner Board

B.5 Commercial Hardware used in the SCTU System

Table B.3: Commercial hardware used in the SCTU system

Block	Device	Main Characteristics
ATJ Solar cell set	15x Emcore Advanced Triple Junction Solar Cells for Space Applications, connected in series in a single solar panel	InGaP / InGaAs / Ge Solar Cells with n-on-p polarity on 140-µm Uniform Thickness Ge Substrate Fully space-qualified with proven flight heritage in LEO and GEO environments Electrical Parameters at AM0 (1353W/M^2 at 28ºC): ▪ V_{oc}: 2.60V ▪ J_{sc}: 17.1mA/cm2 ▪ V_{mp}: 2.30 ▪ J_{mp}: 16.2mA/cm2 ▪ BOL efficiency at maximum power point: 27.5%
Silicon Solar cell set	3x Siemens 103mm standard single crystal silicon solar cells, connected in series in a single solar panel	Square silicon single crystal solar cell grown by the Czochralski method Electrical Parameters at Standard Test Conditions (1000W/m^2, 25ºC and AM1.5): ▪ V_{oc}: 0.585V ▪ I_{cc}: 3.46A
Variable Load	Executive Engineering EE30180A DC Electronic Load	Adjustable and selectable quasi constant power / constant current mode Thermal and over power protection Input Voltage: 0 -55V Input current (adjustable): 0-80 Amperes Maximum Power dissipation: 300 Watts

Pan/tilt unit	Directed Perception Pan-Tilt Unit Model PTU-C46-70	Computer-controlled (RS/232 port) Self calibration upon reset Power consumption can be controlled from host ASCII and binary command modes available DC input from unregulated source Constant current bipolar motor drives On-the-fly position and speed changes Pan: 300 degrees of freedom Tilt: 46 degrees of freedom (bottom), 31 degrees of freedom (top)
Temperature logger	ICP DAS Model CON I-7018	RS/485 interface Voltage, current and thermocouple input Thermocouple: Type J, K, T, E, R, S, B, N, C Channels : 8 differential or 6 differential and 2 single-ended by jumper select Accuracy: ±0.1% Sampling rate: 10 Samples/Second Power Consumption: 1W

General- purpose data logger	Campbell Scientific CR10X	Electrical Interfaces: ▪ Analog Inputs: 12 single-ended or 6 differential (individually configured) ▪ Analog Outputs: 3 switched, active only during measurement ▪ 2 Pulse counters ▪ 3 Switched voltage excitations ▪ 8 control/ digital ports ▪ 1 Serial I/O port ▪ 64Hz Scan rate ▪ 13 A/D bits Stores 62000 data points (non-volatile) 32 kilobytes available to run programs Electrical characteristics ▪ Input voltage: 9.6 to 16V ▪ Current drain (typical): 1.3mA quiescent, 13mA during processing and 46mA during analog measurement
Pyranometer	Kipp and Zonen CM3	Thermopile pyranometer Measurement range: 305 to 2800nm Maximum irradiance: 2000W/m^2 Signal output: 0-50mV Flat spectral response of the full solar spectrum range
Temperature and Relative Humidity Sensor	Campbell Scientific CS500-L	Contains a Platinum Resistance Temperature detector (PRT) and a Vaisala INTERCAP® capacitive relative humidity sensor Temperature measurement range: -40º to 60ºC Temperature Output signal: 0 to 1V Relative Humidity measurement range: 0 to100%

Wind Monitor	R.M. Young 05103	Measures wind speed and direction Wind speed range: 0-60m/s (±0.3m/s accuracy) Wind speed range: 0-360º mechanical, 355º electrical (±3º accuracy) Power: switched excitation provided by the data logger
Spectrophotometer	Ocean Optics SD2000	Two independent channels (master and slave) Spectral Range: 200 to 850nm (master channel); 520-1100nm (slave channel) Cosine corrector disks both channels

B.6 Main Electronic Components used in the SCTU System

Table B.4: Main electronic components used in the SCTU system

Block	Device	Main Characteristics
Current Sensor	F.W. Bell NT-5	Primary nominal current (I_{pn}): 5A Measurement Range: 0 to ±15A (for 3 seconds) Output voltage at $\pm I_{pn}$: ±2.5V Linearity: < ±0.25%
Opto-relays (for control of PC power and PTU power)	2x Grayhill 70G-ODC5	$4000V_{rms}$ optical-isolation $5V_{dc}$ logic 3-$60V_{dc}$ output Current rating (at 45ºC): 3A
PC-controlled opto-relay (solar cells)	Opto 22 Model G4ODC5	$4000V_{rms}$ optical-isolation $5V_{dc}$ logic 5-$60V_{dc}$ output Current rating (at 45ºC): 3A
Switching Relay	Potter & Brumfield KUP-14D15-12	Basic enclosed relay 3C (3PDT) contact arrangement $12V_{DC}$ coil input 10 Amps max
Operational Amplifiers	3x ST Microelectronics TL062N	2 JFET-input operational amplifiers per unit Wide common-mode and differential voltage ranges Output short-circuit protection Slew Rate: 3.5V/µs (typ) *These operational amplifiers are used in the signal conditioner board, implementing a voltage follower in series with an active low-pass filter in each unit*

APPENDIX C CONNECTIONS OF MASS / SCTU FOR ASSEMBLY IN THE FIELD

Table C.5 shows the cable connections needed in the main enclosure when installing the system in the field. Several cables enter the primary enclosure which are connected in one of the three connection locations available in the enclosure.

Table C.5: Main connections in the main enclosure to install the MASS / SCTU system in the field

Cable 0: Power Solar Panel 1 cable *Cable 1*: Power Solar Panel 2 cable *Cable 2*: Battery Cable *Cable 3*: From secondary enclosure *Cable 4*: From temperature logger *Cable 5*: From silicon solar panel (voltage monitoring) *Cable 6*: From ATJ solar panel (voltage monitoring) *Cable 7*: Cable from pyranometer *Cable 8*: Cable from anemometer *Cable 9*: Cable from temperature and humidity sensor	*Connection Location A*: Wire connects in terminal block rack *Connection Location B*: Wire connects in signal conditioner board *Connection Location C*: Wire connects in general-purpose data logger

Cable										**Wire (in Cable)**	**Connects to: (in primary enclosure)**	**Connection location**			**Final electrical Connection in MASS or SCTU hardware (*)**
0	1	2	3	4	5	6	7	8	9			**A**	**B**	**C**	
X										+	1	X			Solar Controller: +
X										-	2	X			Power Solar Panel 2: + (series connection)
	X									+	3	X			Power Solar Panel 1: - (series connection)
	X									-	4	X			Solar Controller: -
		X								-	6	X			Solar Controller: Battery - and power manager board
		X								+	7	X			Solar Controller: Batter + and power manager board
			X							red	Relay +	X			Switching relay in SCTU: + (coil)

			X							Brown	Relay -	X			Switching relay in SCTU: - (coil)
			X							white	Analog Output Vo0	X			Electronic-controlled variable load: control signal
			X							green	Analog Input 0	X			Current sensor: output signal
			X							blue	Analog Input 1	X			Electronic-controlled variable load: internal current sensor output (not used)
			X							Black	G	X			Ground for secondary enclosure
			X							yellow	12V	X			12V for secondary enclosure
			X							orange	-12V	X			-12V for secondary enclosure
				X						green	ICP Logger (green)	X			Temperature transmitter: data -
				X						yellow	ICP Logger (yellow)	X			Temperature transmitter: data +
				X						red	ICP Logger (red)	X			Temperature transmitter: +Vs
				X						black	ICP Logger (black)	X			Temperature data transmitter: Gnd
					X					Green + black3	Analog Input 5	X			Voltage monitoring signal in solar panel
					X					White + black5	Analog Input 6	X			Voltage monitoring signal in solar panel
					X					red	Analog Input 7	X			Voltage monitoring signal in solar panel
					X					black1	Analog Ground	X			Voltage monitoring ground in solar panel
						X				black1	1		X		Voltage monitoring ground in solar panel
						X				red	2		X		Voltage monitoring signal in solar panel
						X				white + black5	3		X		Voltage monitoring signal in solar panel
						X				green + black3	4		X		Voltage monitoring signal in solar panel
							X			clear	G			X	

							X			red	1H			X	
							X			blue	1L			X	
							X			white	AG			X	
								X		clear	G			X	
								X		black	G			X	
								X		red	P1			X	
								X		blue	E1			X	
								X		white	AG			X	
								X		green	2H			X	
									X	clear	G			X	
									X	black	3H			X	
									X	red	12V			X	
									X	green	AG			X	
									X	brown	2L			X	

(*) Shows the final internal wiring destination of the terminal block connection. Connections such as A/D and D/A interface may be easily changed by modifying the programming code. Values are shown as a reference and are current on the publication date.

Table C.6: Main connections in the main enclosure to install the MASS / SCTU system in the field

Terminal #	**Connection**
4	ATJ Power: red (V+)
5	ATJ Power: white (V-)
6	Silicon Power: red (V+)
7	Silicon Power: white (V-)
8	Signals: red (+ coil)
9	Signals: brown (- coil)
10	Signals: blue (variable load current signal)
11	Signals: white (variable load control)
12	Signals: green (current sensor signal)
13	Signals: yellow (12V)
14	Signals: orange (-12V)
15	Signals: black (logic ground)

Table C.6 shows the cable connections needed in the secondary enclosure when installing the SCTU system in the field. Three cables enter the secondary enclosure, named as “ATJ Power” (power signal from ATJ solar cell set), “Silicon Power” (power signal from silicon solar cell set) and “Signals” (signals and power for/from the main enclosure).

APPENDIX D DETAILED PIN OUT OF MASS / SCTU SYSTEMS

The following tables shows every connection between devices in the complete MASS / SCTU system. These tables are provided for reference purposes only and should not be changed for regular operations, unless a severe electronic redesign is being made or for fault detection.

D.1 Terminal blocks rack in the main enclosure

All cables connected to individual blocks are shown below.

Table D.7: Connected devices per terminal blocks in main enclosure

Block Number	Detail of Connected Devices
1	▪ + Solar Panel 1 (Power Supply) ▪ Solar + (Solar Charger)
2	▪ - Solar Panel 1 (Power Supply) ▪ Terminal Block 3
3	▪ + Solar Panel 2 (Power Supply) ▪ Terminal Block 2
4	▪ - Solar Panel 2 (Power Supply) ▪ Solar – (Solar Charger)
5	▪ GND for Power Manager Card ▪ Battery – (Solar Charger) ▪ Terminal Block 6
6	▪ Battery - ▪ Terminal Block 5
7	▪ Battery + ▪ Terminal Block 8
8	▪ +24V for Power Manager Card ▪ Battery + (Solar Charger) ▪ Terminal Block 7
RELAY +	▪ To Solar Experiment: + connection of switching relay ▪ (Solar Panel Chooser) (red) ▪ SS-Relay Rack Opto-22: Field Connection 7
RELAY -	▪ To Solar Experiment: - connection of switching relay ▪ (Solar Panel Chooser) (brown) ▪ Terminal Block B or C
ICP Logger Green	▪ RS232/RS485 Converter – TD(A) ▪ Temperature Logger – “DATA –“
ICP Logger Yellow	▪ RS232/RS485 Converter – TD(B) ▪ Temperature Logger – “DATA +”
ICP Logger Red	▪ Terminal Block 12V ▪ Temperature Logger – “+Vs”

ICP Logger Black	▪ Terminal Block B or C ▪ Temperature Logger – “GND”
G	▪ Terminal B or C, equivalent to GND from Solar Charger ▪ Black from main cable from solar experiment
5V	▪ 5V available from Power Supply Card – PC /104
12V	▪ 12V available from Power Supply Card – PC /104 ▪ Yellow from main cable from solar experiment
-12V	▪ -12V available from Power Supply Card – PC /104 ▪ Orange from main cable from solar experiment
Digital Output DO0 / Channel A	Opto Isolator – Field side, Pin #7
Analog Channel Output Vo0	Solar Experiment Main Cable (White) (Control Signal for the Variable Load)
Analog Channel Input 0	Solar Experiment Main Cable (Green) (Input From External Current Sensor)
Analog Channel Input 1	Solar Experiment Main Cable (Blue) (Input from Variable Load's Internal Sensor)
Analog Channel Input 2	Red Cable from Signal Conditioner Card (Voltage reading of Panel 1 of ATJ panels)
Analog Channel Input 3	Green Cable from Signal Conditioner Card (Voltage reading of Panel 1+2 of ATJ panels)
Analog Channel Input 4	Yellow Cable from Signal Conditioner Card (Voltage reading of Panel 1 of ATJ panels)
Analog Channel Input 5	Silicon Panel Signal Cable: Green+Black 3
Analog Channel Input 6	Silicon Panel Signal Cable: White+Black 5
Analog Channel Input 7	Silicon Panel Signal Cable: Red
Analog Ground G	Silicon Panel Signal Cable: Black 1

Note: Details marked in **BOLD** are connections that have to be made recurrently, each time the Solar Station is installed. Details not in bold, are permanently connected and should remain untouched, unless the weather station is disassembled completely.

D.2 Connections in Solar Controller

Table D.8: Cable connections in solar controller

From	To
Load -	Terminal Block B or C
Load +	Terminal Block A
Solar +	Terminal Block 1
Solar -	Terminal Block 4
Battery +	Terminal Block 8
Battery -	Terminal Block 5
Sense +	Short Circuit to Battery +
Sense -	Short Circuit to Battery -

D.3 Connections in current measuring board (secondary enclosure)

Table D.9: cable connection in current sensor board

Pin #	Connection
1	I Sensor - Iout
2	I Sensor - Iin
3	Output I sensor
4	Ground
5	-12V
6	12V

D.4 Connections in Signal Conditioner Board

Table D.10: Cable connections in signal conditioner board

ATJ voltage monitoring cable	**Connects to:**
black 1	1
red	2
white + black 5	3
green + black 3	4

D.5 Connections in terminal blocks rack in the secondary enclosure

Table D.11: Cable connections in terminal blocks of the secondary enclosure

Pin #	**Connection**
1	NC
2	NC
3	NC
4	V+ ATJ Panels
5	Common V- for ATJ & Si Panels
6	V+ Si Panels
7	Common V- for ATJ & Si Panels
8	Relay - Control V+ (Coil) (Red)
9	Relay - Control V- (Coil) (Brown)
10	Output from internal I sensor included in Variable Load (Blue)
11	Control Signal for Variable Load (White)
12	Output from external I sensor (Green)
13	12V (Yellow)
14	-12V (Orange)
15	Logical Ground (Black)

D.6 Connection of opto-relays in main enclosure

The three opto- relays located in the main enclosure (PC power, PTU power and solar panel control) are installed in a 4-channel I/O module rack. Figure D.8 shows the connection scheme of interface with the rest of the system.

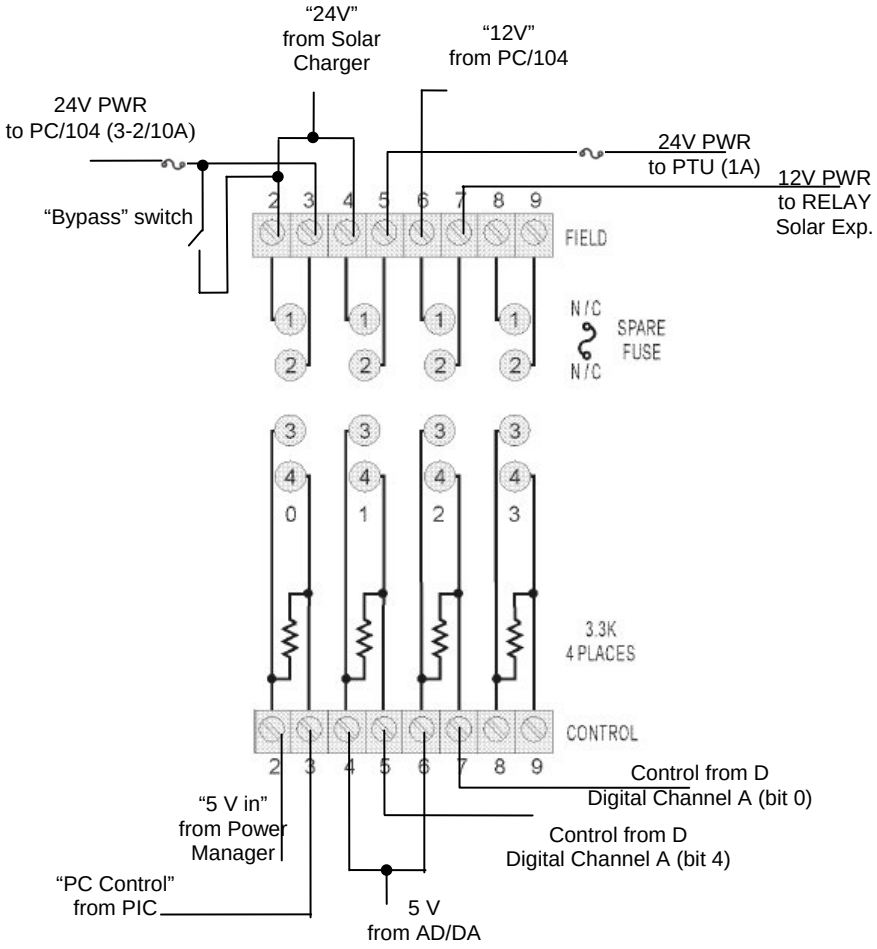

Figure D.8: Cable connections of the three opto-relays of the system mounted in a 4-channel I/O module rack

D.7 Connection of solar cell testing sets

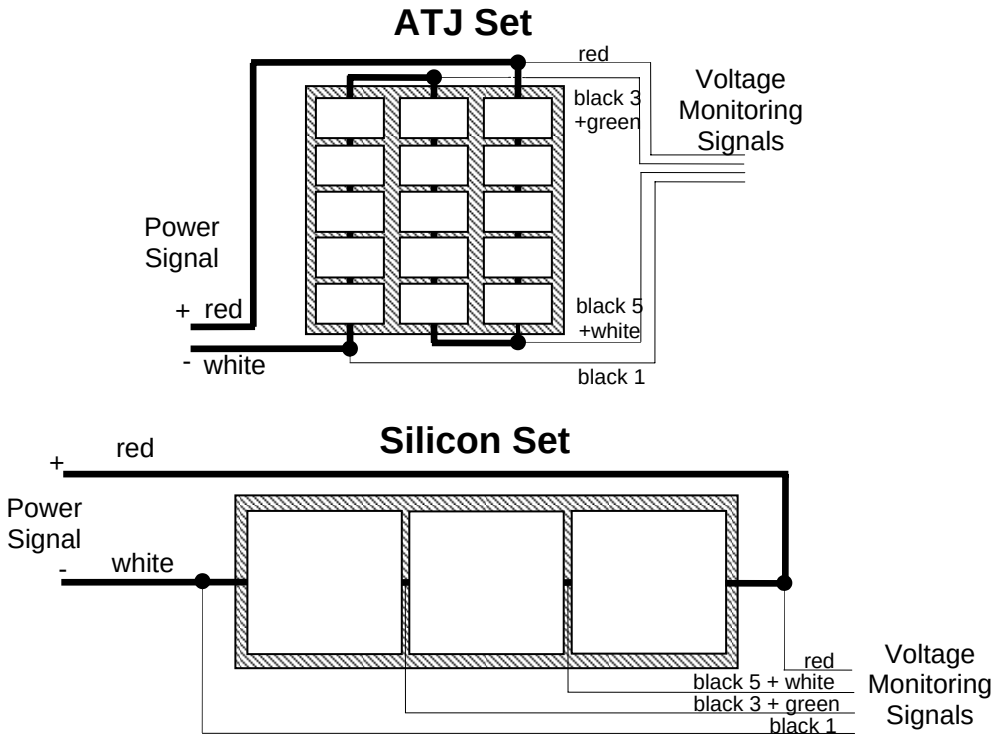

Figure D.9: Cable color code of ATJ and silicon solar cell sets

APPENDIX E SOFTWARE-SPECIFIC DETAILS

E.1 General Information about the processes

The central computer of the system runs the MASS and SCTU processes under Redhat 7.3. The complete programming code of the software can be located in the hard drive at the following location:

```
/home/mwagner/atacama/src/solarStation/
```

Code related to the MASS (user interface and power manager systems) can be found in the *PIC* subdirectory.

The system runs two concurrent processes, called “pwrmngd” (MASS process) and “solarStation” (SCTU process). Only the MASS process needs to be executed, automatically running the “child” SCTU child process by forking procedures of Linux. On the current setup the pwrmngd process is executed automatically on bootup by the rc.local file. Manual execution may be performed executing the following command:

```
/usr/sbin/pwrmngd
```
[2]

E.2 Generated Data Files

The SCTU process generates several data files which are stored at the following location:

```
/data/weatherStation/
```

---

[2] In case of recompilation the pwrmngd file must be generated by a “`make install`” execution.

Three subdirectories are available which store data on a daily basis:

- dailyLogs/: stores tabulated weather text data files that can be directly imported to Matlab or Octave.
- SolarPanels/: stores tabulated solar cell data from the SCTU, which can be directly imported to Matlab or Octave. Files are stored in the `Automatic.Data` or in the `Manual.Data` subdirectories, depending if they were automatically generated or using the auxiliary process for manual control, respectively. All data captured on a single day is stored in a subdirectory containing the date in its name.
- dailyPlots/: stores Octave-executable scripts that automatically generate frequently-required plots (weather, I-V curves, etc). Plots are generated once all the weather data for a single day has been captured.

The `/data/weatherStation/`directory additionally contains two files. The `usergnted.m` contains a filtered data set which was manually generated by the user after executing the appropriate option onh the user interface system. The `workLog.dat` file is a temporary file that stores weather data for the last ten days (older data is automatically removed). The `workLog.dat` file is internally used by the system for automatically filtering data (e.g. generation of `usergnted.m`), but may also be used by the user for simplifying manual multiple-day data processing procedures.

E.3 Weather Data

Weather log data is written on a single daily-file with the following format:

```
101  (year)  (day of year)  (Unix time)  (insol, W/m²)  (tot.energy, kJ),  0,  0
102  (year)  (day of year)  (Unix time)  (wind, m/s)  (wind, m/s),  (wind_d1),  (wind_d2)
103  (year)  (day of year)  (Unix time)  (temp, ºC)  (humidity, %),  0,  0
```

E.4 Solar Cell Data

Solar cell data files include relevant information in the filename for file ordering. The file format is the following:

`nº-type-position-time.log`

- nº: increasing sequential number indicating the experiment of the day.
- type: defines the solar panel used for the experiment (“ATJ” or “Si”).
- position: indicates the desired orientation of the solar cells in the format of a sequential position number defined in the programming code. May be “i0”, “i1”, …. “in” (predefined positions) or “iSun” (sun-oriented).
- time: time of the day in HH.MM format

Additionally, relevant parameters related to the execution of the experiment are included as a header in the text file. Captured data is preceded by a “%” sign (ignored comments for Matlab / Octave). Parameters include the real orientation of the solar cells, desired orientation in degrees and settle measuring time, among other relevant factors.

Captured data is logged with the following format:

```
(current[A])  (voltage 1 [V])  (voltage 2 [V])  (voltage 3 [V])  (temp1[ºC]) (temp2[ºC])
```

“Voltage x” corresponds to the different voltage measuring signals in increasing voltage order, being “v3” the voltage across all the solar cells connected in series (see Appendix D.7). “Temp x” corresponds to the temperature of the two thermocouples in the solar cell set.

Furthermore, the last row in the data file includes the global irradiance in W/m^2 measured during the execution of the experiment. The parameter is repeated in the six different columns to help data processing.

E.5 Main programming code files

The main programming code files written specifically for the MASS / SCTU are discussed below. General-purpose libraries used in the system are omitted.

- `dataLogger {.h, .cc}`: includes all functions that interact with the general-purpose data logger. Includes functions to download data, read current weather, read current date (time server) and for weather log file generation. The

`writeDataLogger(FILE *logFile)` function must be modified to change the format of output weather logs.

- `panelTest {.h, .c}`: contains functions related to the AD/DA board and temperature transmitter, including functions to read the A/D, write the D/A, write the digital output and read the thermocouple inputs. All these functions are used in `readPanel.cc`.
- `pwrcomm {.h, .c}`: contains all definitions and functions needed to achieve inter-process communication (IPC messages), used by the SCTU (solarStation) process.
- `readPanel {.h, .cc}`: contains all constants and functions needed to capture the electrical data related with the solar cell testing experiment. It controls the variable load, captures current and voltage data and generates log files. The `writePanelData(FILE *logFile, RADIANS ptuPan, RADIANS ptuTilt)` must be modified in order to change the format of output weather logs. The .h file contains important definitions related to settle times, voltage divider scaling factors, calibration factors for current measurement and operation range of the variable load for each set of solar cells.
- `solarStation.cc`: contains the `main` function of the SCTU (solarStation) and NASA SPICE related-functions needed to track the sun.
- `solarStationPTU {.h, .cc}`[3]: defines the `SolarStationPTU` class, which encapsulates the functionality of the Directed Perception PTU-46-70, on which the testing solar cell sets and spectrophotometer are mounted.
- `weatherStationSerialPorts.h`: defines serial ports used by MASS/SCTU systems.
- `PIC/src/prococol {.h, .cc}`: contains functions related with the communication protocol between the MASS (pwrmngd process) and the PIC microcontroller. It includes functions called on a recurrent-basis, including the connection procedure, reading values stored in the EEPROM memory of the

[3] Code written by Michael Wagner, Senior Research Programmer from the Robotics Institute of Carnegie Mellon University, member of the Life in the Atacama team.

microcontroller, checking user-generated commands, checking battery voltage, checking current time related to the power-off schedule and performing shutdown procedures.

- `PIC/src/pwrcomm {.h, .c}:` contains all definitions and functions needed to achieve inter-process communication (IPC messages) used by the MASS (pwrmngd) process.
- `PIC/src/pwrmngd {.h, .c}`: contains the *main* function of the MASS (pwrmngd) process. It executes the SCTU (solarStation) process by fork procedures of Linux and implements the complete communication protocol with the PIC microcontroller.
- `PIC/src/solarControl`.c: contains all functions needed for the manual operation of the solar experiment. Compilation generates an independent executable file in the `PIC/bin` subdirectory, which allows the user to orient the solar panels and perform the solar experiment through a prompt (automatic execution is suspended). The generated program does not access the hardware directly, instead it generates IPC messages, indirectly performing actions in the `solarStation` process.

E.6 About Log Files and Time Management

The general-purpose data logger permanently logs weather data in its internal memory, adding a timestamp of its internal clock. When the PC is online all information stored in the data logger is transferred to the computer. When transferring the data, the computer is unable to determine in terms of its internal PC clock the exact time when the data was generated due to inexistent synchronization between clocks. Exact synchronization between the PC and data logger is avoided due to its complex implementation, specially for long periods of time.

As it is crucial that all data logged by the MASS/SCTU systems is referred to a single clock, the general-purpose data logger is used additionally as a time server. All logs are generated querying the data logger for the current time, including logs related to the electrical data of the solar cell testing experiment. The MASS software automatically transforms and logs the date format of the data logger in terms of standard “Unix time” (elapsed number of seconds since 00:00:00 of January 1st 1970, UTC time).

APPENDIX F IMPLEMENTED PROTOCOL FOR PC – MICROCONTROLLER COMMUNICATION

The PC and the microcontroller communicate through a standard RS-232 serial line. The PC works in a "Connection Request / Connected" system, having different options available according to its actual connection state. The system will try to maintain a connected status during all the time possible. The microcontroller does not specifically have a "connected" status, but it defines its internal state according to the last command received from the PC and position of the relays (opened-closed).

Kinds of messages ("x" represents a number between 0-9):

1x: Informative, deal with connection status of the PC/104.
2x: Synchronous commands from the PC to the PIC
3x: Asynchronous commands from the PC to the PIC
4x: Synchronous commands from the PIC to the PC
5x: Asynchronous commands from the PIC to the PC

All messages being communicated will have the following structure:

*xxmmmm#

(* is the starting character for a message,
xx is the kind of message,
mmmm: is the "body" of the message (additional information being sent with kind of message). Different kinds of data will be separated by a semicolon (;). Different lengths are accepted, but should be shorter than 100 characters,
#: ending character for delimiting the end of a message).

All possible messages are described in Table F.12.

Table F.12: All possible messages in computer – microcontroller communication protocol

	Message	**Description**
Informative	*10#	Connection Request from PC – PC is not connected. Will be sent every 5 seconds in case an ACK is not received. NOTE: PIC GOES TO MAIN MENU AUTOMATICALLY.
	ACK10	ACK to "10"
	*11#	From the PC: Should I turn on all the experiments?
	ACK11.0	Answer to 11: no, don't turn on experiments.
	ACK11.1	Answer to 11: yes, turn on experiments.
	*12#	From the PC: What is the battery voltage limit?
	ACK12.XX	Answer to 12: voltage, in volts*100 (no decimals included)
	*13#	From the PC: What is the length of the night?
	ACK13.XX	Answer to 13: night length, in minutes
	*14#	From the PC: At what time does the night start?
	ACK14.HH:MM	Answer to 14 (hours & minutes)
	*15#	From the PC: What is the PTU Orientation?
	ACK15.XX	Answer to 15: PTU Orientation in degrees* 100
	*16#	From the PC: What is the PTU Slip?
	ACK16.XX	Answer to 16: PTU Orientation in degrees* 100
	*17#	From the PC: What is the Latitude?
	ACK17.XX	Answer to 17: Latitude* 100
	*18#	From the PC: What is the Longitude?
	ACK18.XX	Answer to 18: Longitude* 100
	*19#	From the PC: PC was turned on "normally"?
	ACK19.0	Answer to 19: No, it was turned at night.
	ACK19.1	Answer to 19: Yes
From PC to PIC	*20x#	From the PC: Temperature is being sent (ºC*100, no decimals). RANGE: -99.99 to 99.99ºC
	*21x#	From the PC: % Relative Humidity is being sent (%*100, no decimals). Limit: 100.00%
	*22x#	From the PC: W/m^2 is being sent (*10, no decimals). LIMIT: 3276.7 W/m^2
	*23x#	From the PC: Wind (m/s) is being sent (*100, no decimals). Limit: 327.67 m/s

	*24x#	From the PC: Leaf sensor measurement is being sent (*10, no decimals). LIMIT: 100.0%
	*25x#	From the PC: Informing battery level in Volts*100 (this is the same measurement received from the PIC but transformed into Volts according to voltage divider and supply voltage). LIMIT: 99.99V
	ACK2x.V	From the PIC: Informing actual battery level. This message will be sent as an answer to any "2x" message (V=in "ticks" between 0-1024).
	*30x#	Auto shutdown request; turn back on tomorrow (to be used when turning off at night) in "X" minutes. If x= -1, do not turn on again. Limit: 999 minutes
	*31x#	Auto shutdown request, PIC decides when to turn system on again (low battery limit). Message should include for how much more time it should monitor the batteries. If that time occurs, delay turning on for tomorrow. NOT USED.
From PIC to PC	*50x#	Shut down PC now. X=1 to turn back on tomorrow, X=0 turning off is forever.
	*51#	Command was removed (NOT USED)
	*52#	Shut down solar experiment now (for today).
	*53#	Point PTU to the sun (to manually take a spectrophotometry).
	*54x#	Generate plots now, for "x" hours. If "X"= -1, generate plots for today.
	*55#	User has updated configuration values stored in the EEPROM, so PC should ask for these values again.

F.1 Behavior with unknown messages and timeouts

Microcontroller: Only answers to known commands ignoring unknown messages. If 100 continuous characters are received without "*" and "#", the received message is discarded and waits for a new message. If no messages are received from the PC in 10 seconds, assumes communication problems and displays an error on the LCD screen. User generated messages (asynchronous messages) don't have a timeout nor expect an acknowledge. The PIC does not know the connection state of the PC (connected/connection request) and will always answer to ANY command received, even if it is a command that is not expected in the actual state from the PC.

PC: if unexpected command is received returns to "not connected / connection request" status. If 100 characters are received with no "*" and "#", data is assumed as erroneous and returns to the not connected state. Each sent message has a timeout, and repeats it every "x" seconds if no acknowledge is received.

APPENDIX G IMPLEMENTED USER-INTERFACE MENUS

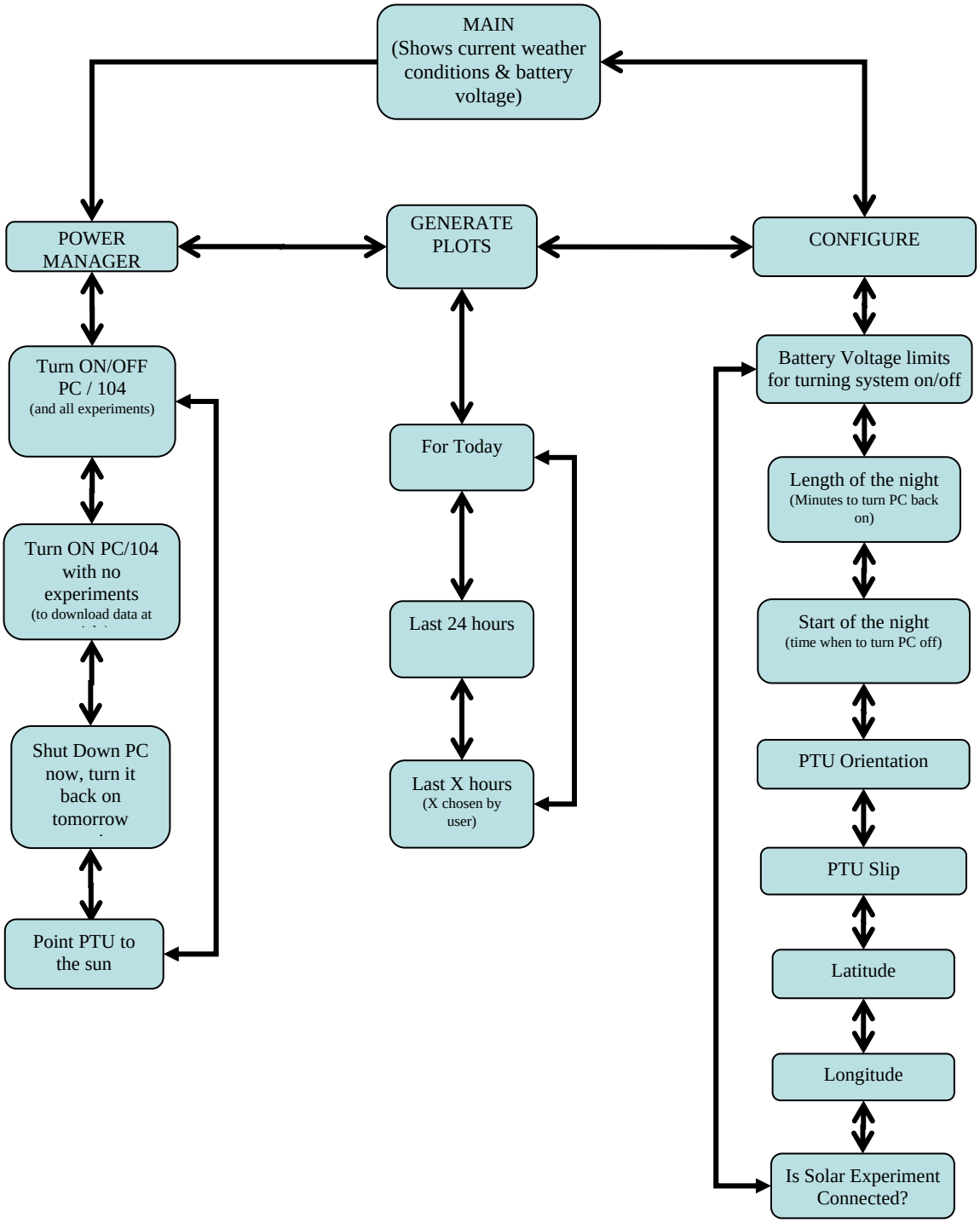

Figure G.10: Implemented menus in user-interface system